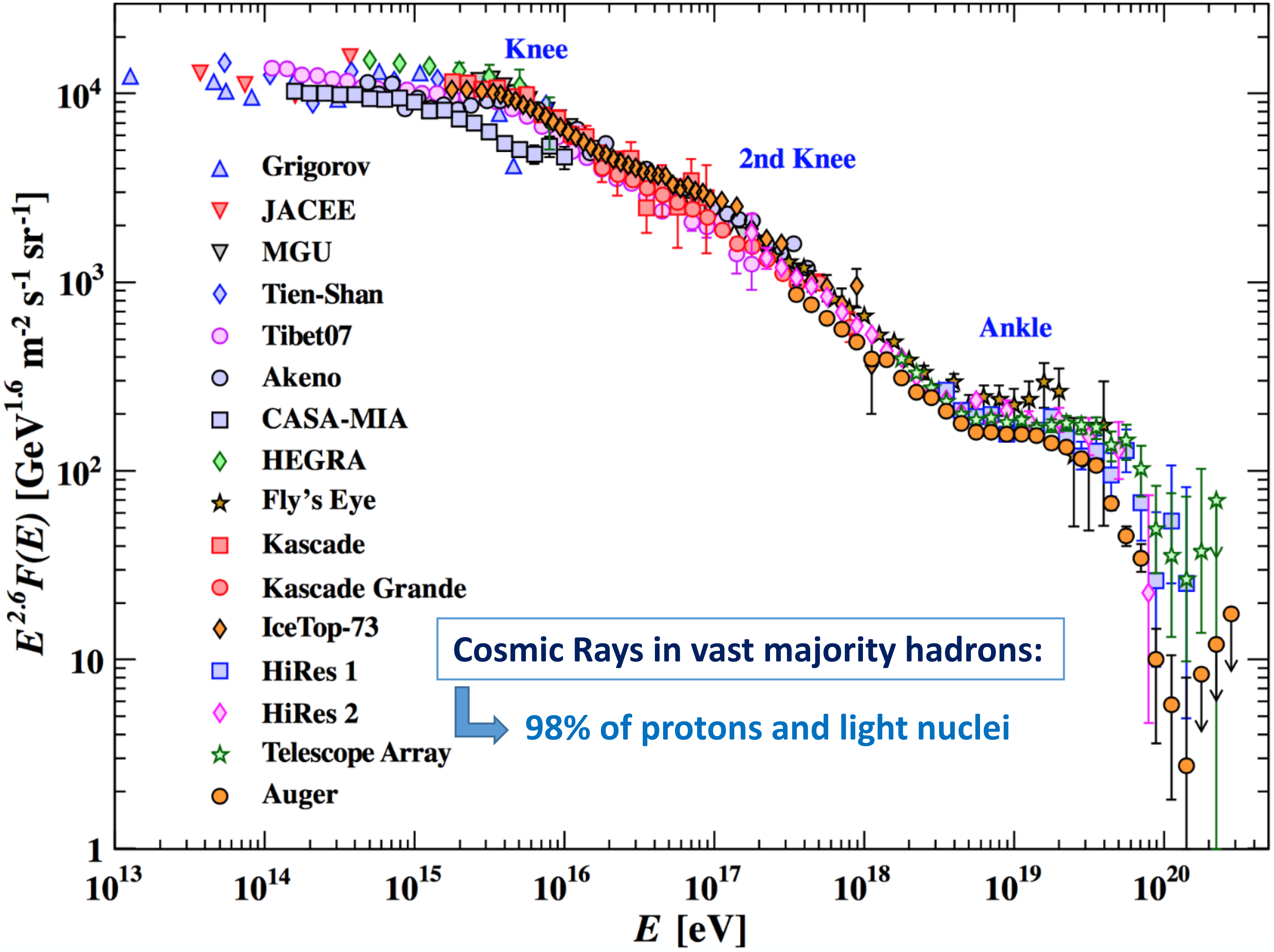
Neutrino Physics and Astrophysics with ANTARES and KM3NeT

Mukharbek ORGANOKOV

19 September 2017

Scientific motivations



Cosmic Rays in vast majority hadrons:

98% of protons and light nuclei

CRs detected on Earth up to extremely high energies: 10^8 TeV

hadronic accelerators exist, but where?

Cosmic Rays:
- Hard to study sources due to deflection by magnetic fields
- Large time delay w.r.t. optical signals

Acceleration of protons by 1st-order diffusive Fermi mechanism at the shock.

Energy loss processes during acceleration:

- **in dense radiation fields:**

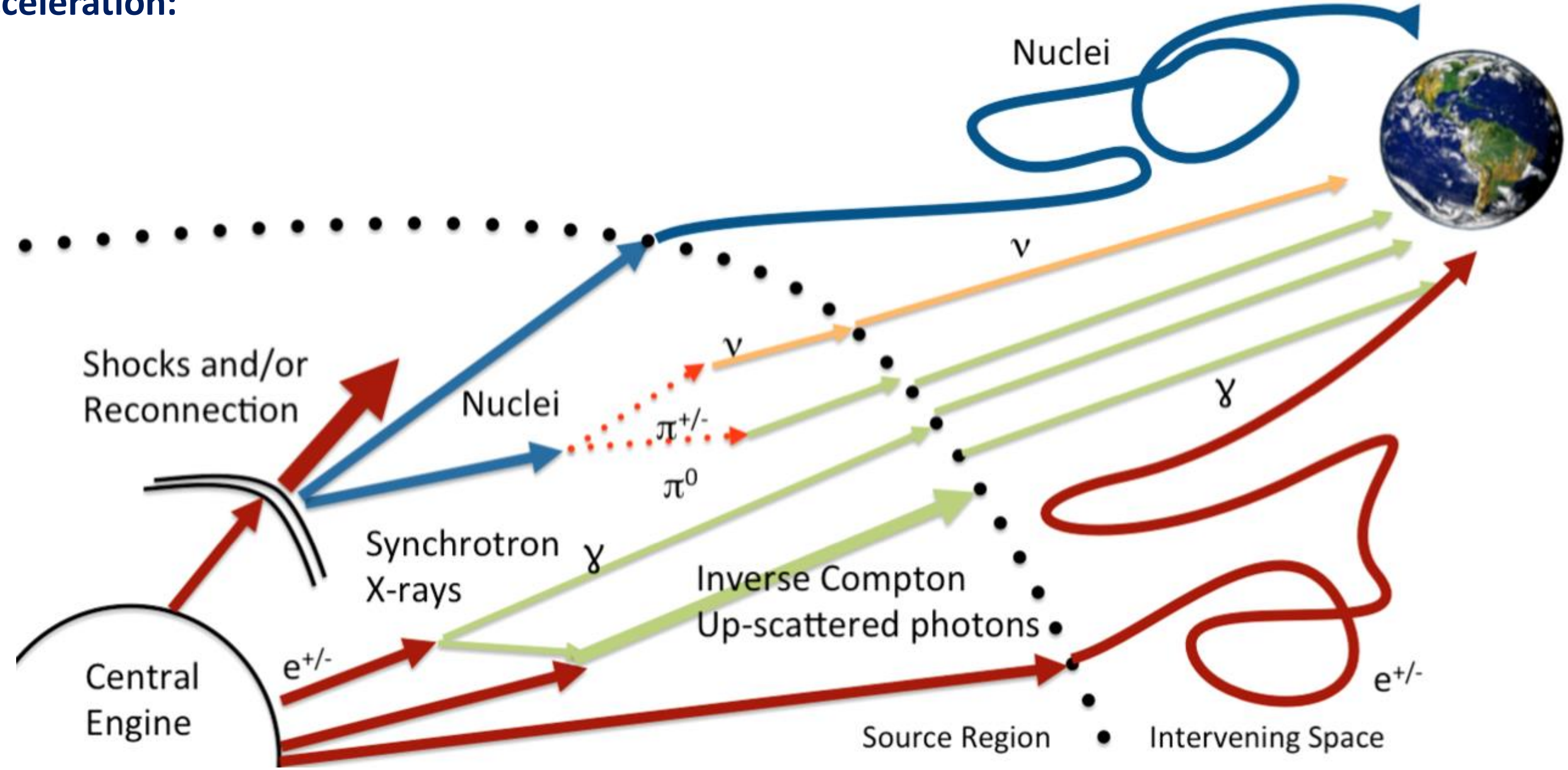
  $p\gamma \rightarrow \Delta^+ \rightarrow p\pi^0, n\pi^+$

  $p\gamma \rightarrow N\pi, \ldots$

- **in interstellar medium gas:**

  $pp \rightarrow pn\pi^+, pp\pi^0, \ldots$

  $pn \rightarrow pp\pi^-, pn\pi^0, \ldots$



γ / ν relation via π-decay:

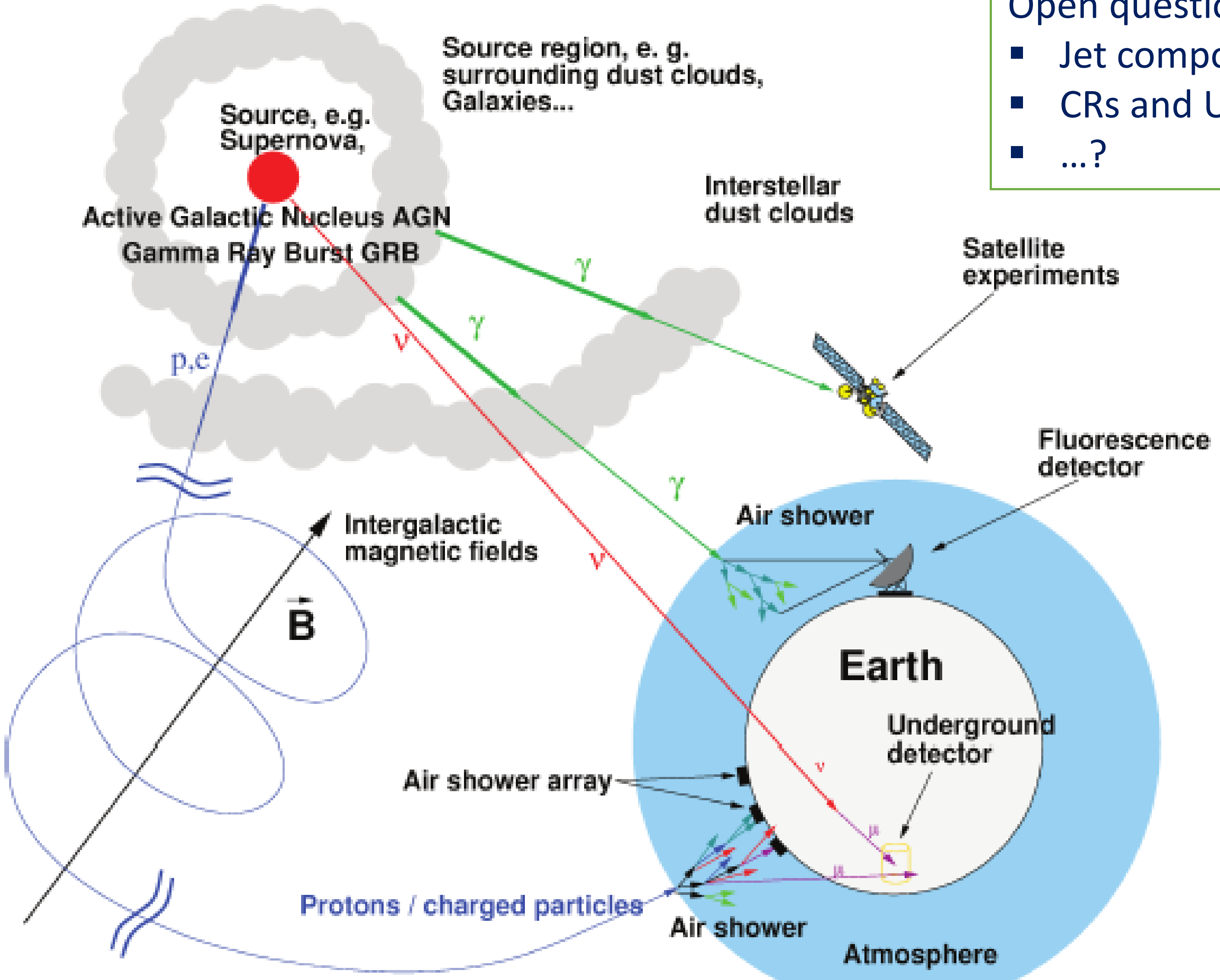
$\pi^0 \rightarrow \gamma\gamma$

$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\nu_\mu\overline{\nu_\mu}$

$\pi^- \rightarrow \mu^-\overline{\nu_\mu} \rightarrow e^-\overline{\nu_e}\nu_\mu\overline{\nu_\mu}$

Neutrino flavour:

$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = (1:2:0)_{Source} \xrightarrow{osc} (1:1:1)_{Earth}$



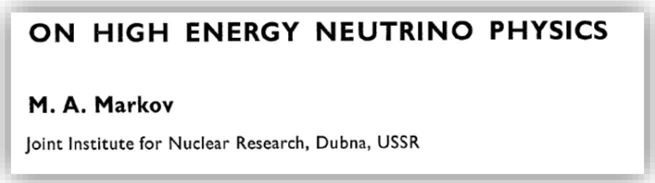
Link CR / γ / ν: Hadronic, Leptonic and Lepto-hadronic models.
Open questions:

- Jet composition?
- CRs and UHECRs origin?
- …?

Cosmic neutrinos:
Possibly produced in the interaction of high energy nucleons with matter or radiation.
Are an advantageous messengers!

- not deflected by magnetic fields:
  points back to the source
- not absorbed by interstellar medium:
  original spectrum

M.A. Markov, ICHEP 1960



ON HIGH ENERGY NEUTRINO PHYSICS

M. A. Markov

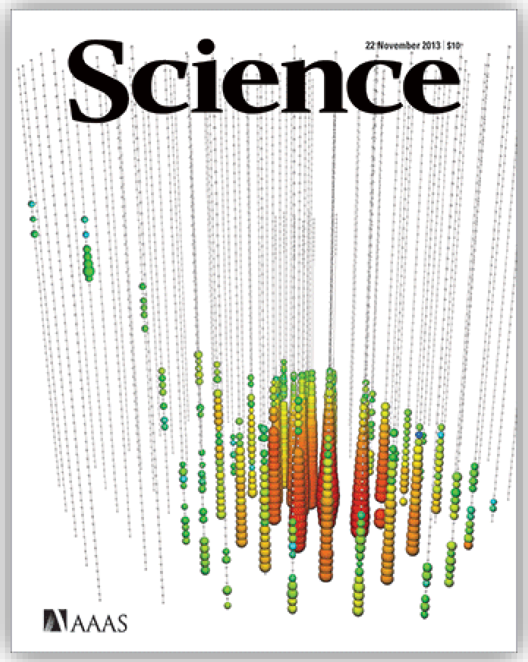
Joint Institute for Nuclear Research, Dubna, USSR

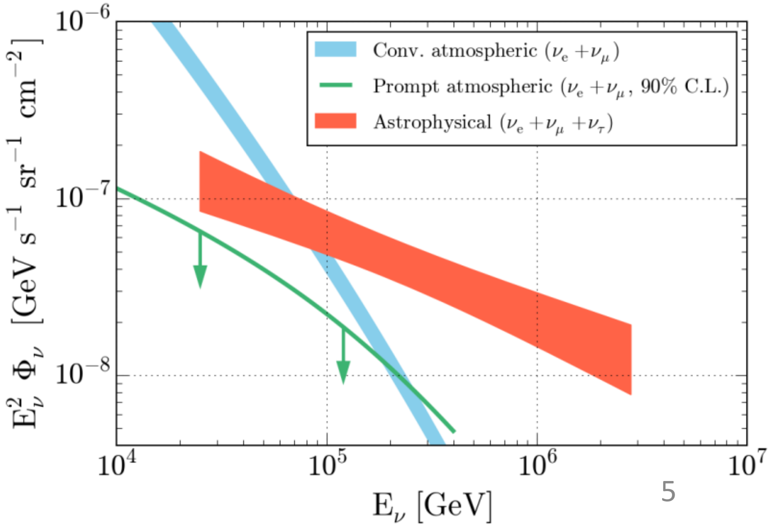
> *"In the papers by Zheleznykh and myself (1958, 1960) possibilities of experiments with cosmic ray neutrinos are analyzed. We have considered those neutrinos produced in the earth's atmosphere from pion decay. From the known μ spectrum the neutrino energy spectrum is reconstructed. We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation. We consider μ mesons produced in the ground layers under the apparatus."*

IceCube, Science 2013

Neutrinos are thought to be produced in astrophysical sources outside our solar system but, up until recently, they had only been observed from one supernova in 1987.

22 Nov 2013 IceCube collaboration reported data obtained between 2010 and 2012 and reveal the presence of a HE neutrino flux containing the most energetic neutrinos ever observed (28 events at energies 30−1200 TeV).



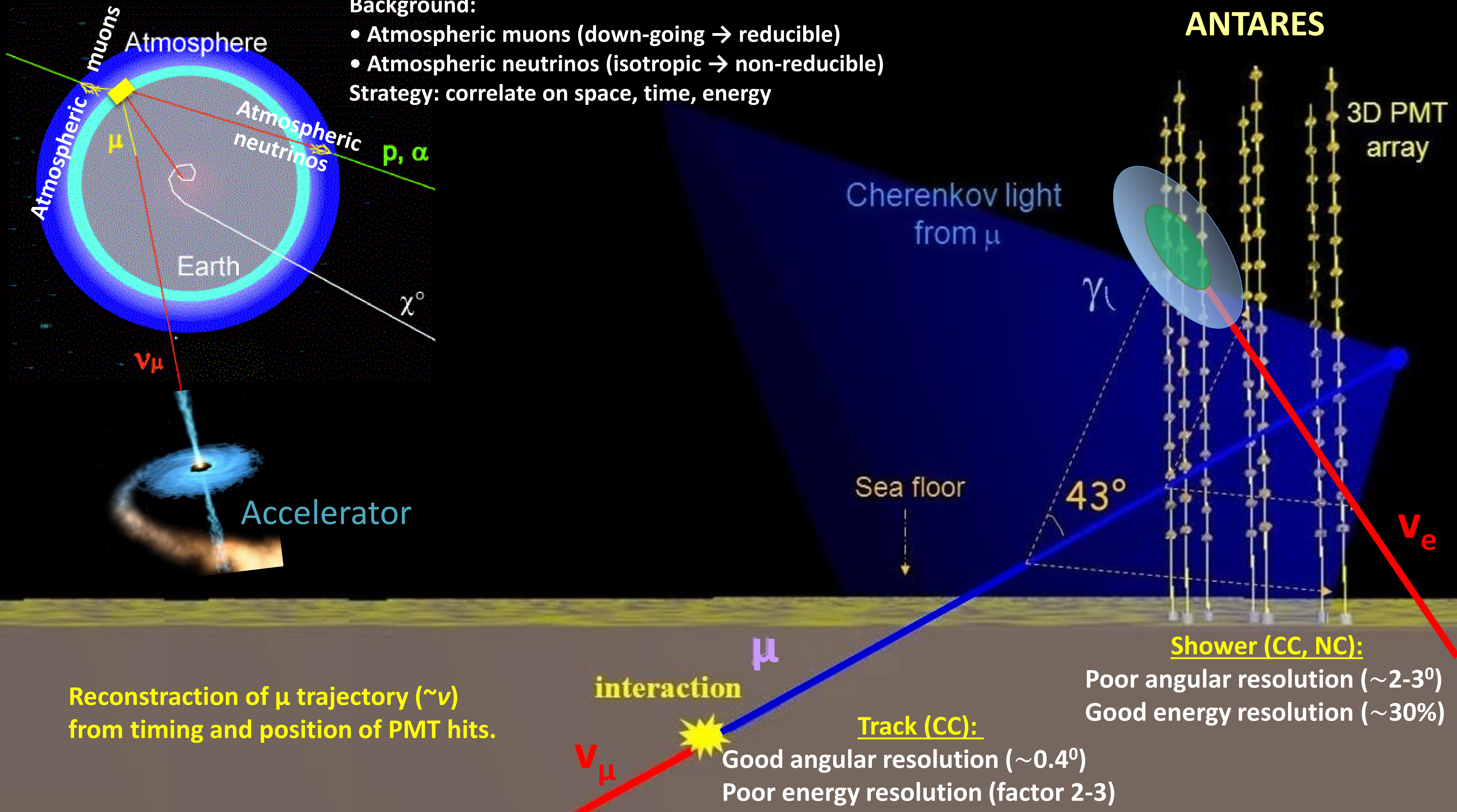


Astrophysical neutrino flux: $E^{-2.50 \pm 0.09}$, for 25-2800 TeV.
A continuous power-law spectrum E^{-2}, which is a popular benchmark model, is excluded with a significance of 3.8σ.

ANTARES

Background:
- Atmospheric muons (down-going → reducible)
- Atmospheric neutrinos (isotropic → non-reducible)

Strategy: correlate on space, time, energy



Reconstruction of μ trajectory (~*ν*) from timing and position of PMT hits.

Track (CC):

Good angular resolution (~0.4^0)

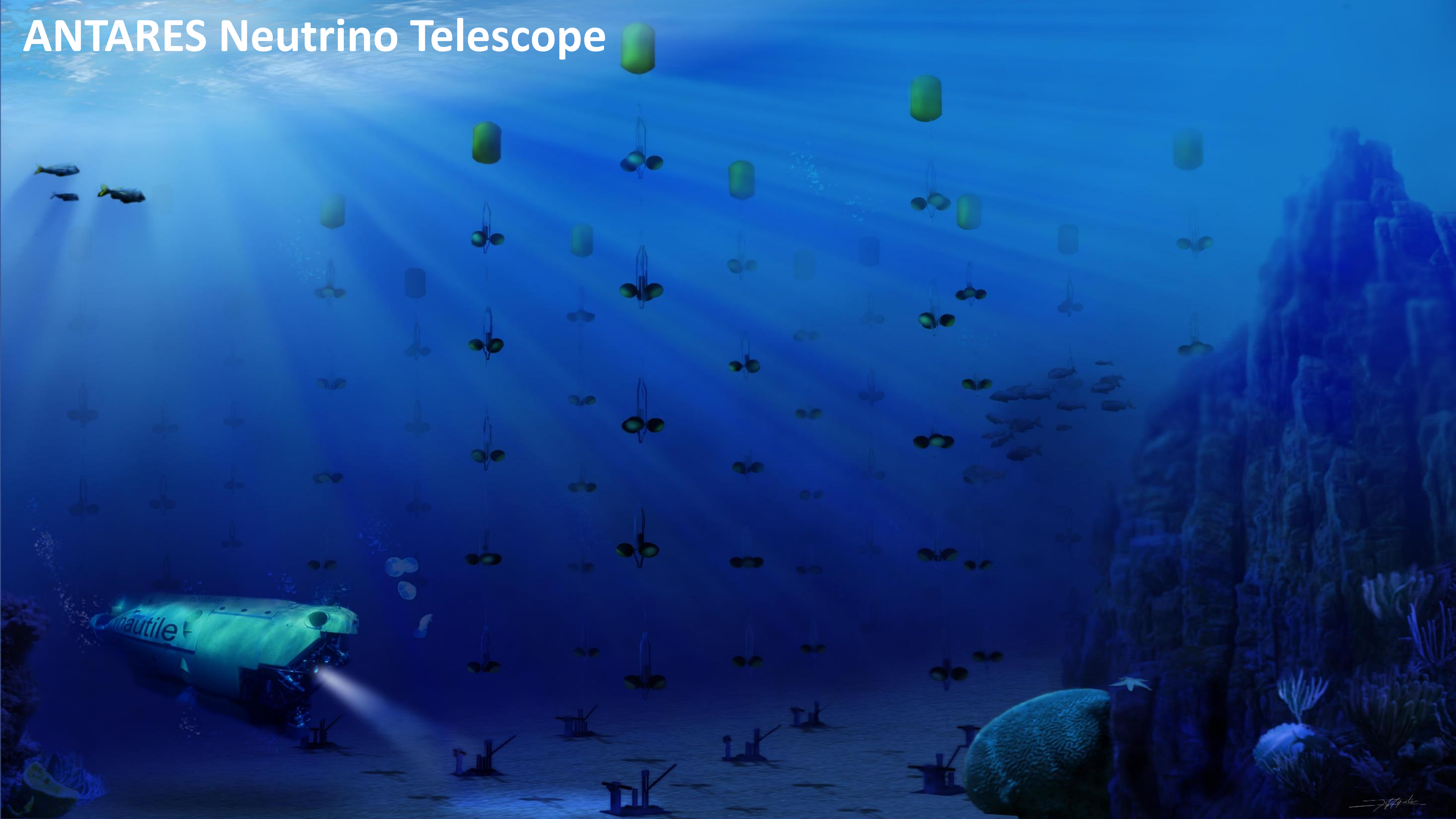
Poor energy resolution (factor 2-3)

Shower (CC, NC):

Poor angular resolution (~$2\text{-}3^0$)

Good energy resolution (~30%)

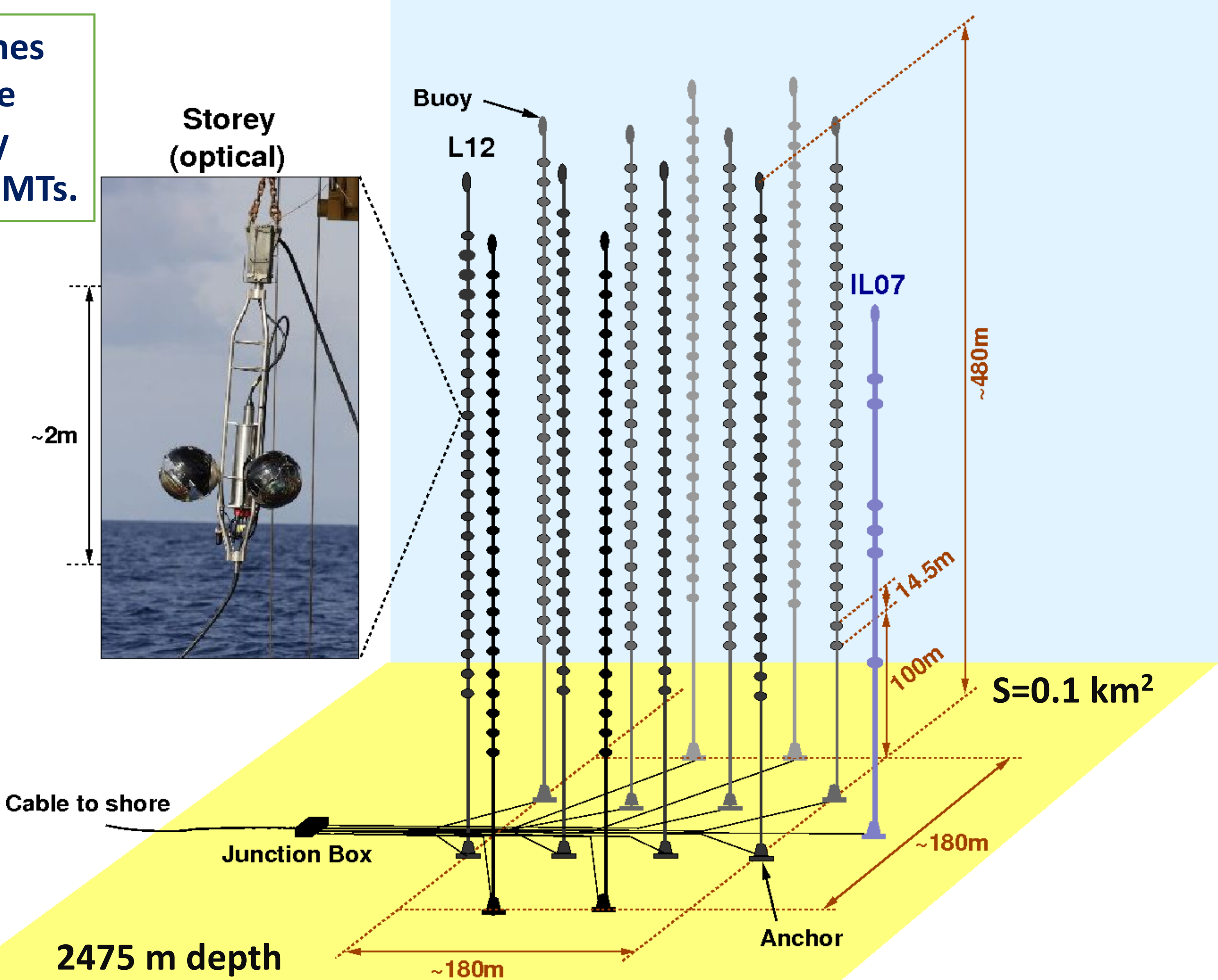
ANTARES Neutrino Telescope



ANTARES, *Astronomy with a Neutrino Telescope and Abyss environmental RESearch*
– 1st step toward the network of km3 scale neutrino detectors KM3NeT, composed of:
ARCA, *Astroparticle Research with Cosmics in the Abyss (Italy)* dedicated to HEN, study of cosmic neutrinos from astrophysical sources
ORCA, *Oscillation Research with Cosmics in the Abyss (France)* dedicated to LEN, determination of neutrino mass hierarchy with atmospheric ν

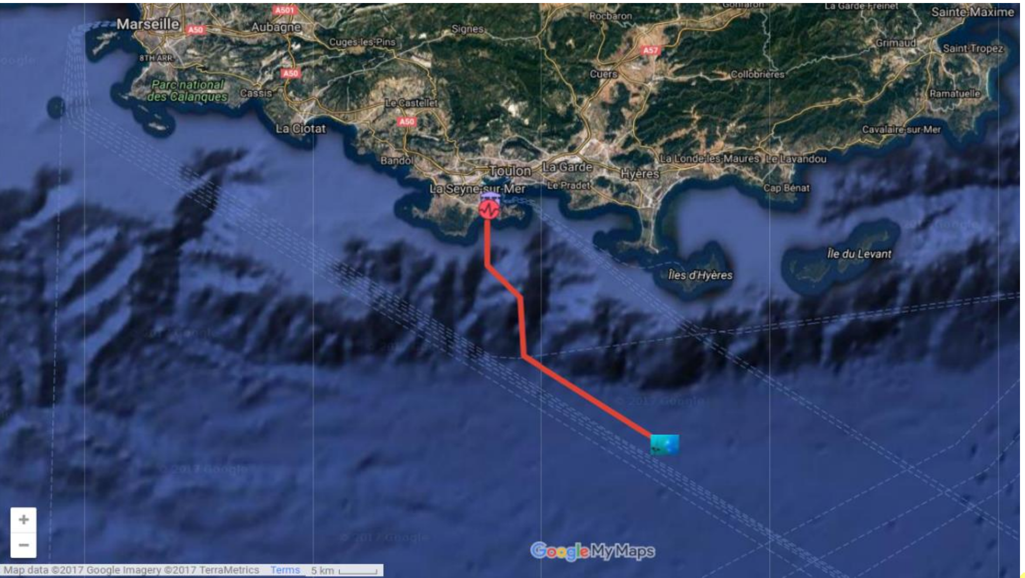
- Data taking: since 2008
- Real-time data processing
- Median angular is
  0.4^0 for E^{-2} spectrum for tracks
  2^0-3^0 for 1-1000 TeV for showers.
- Effective area ~$1 m^2$ at 30 TeV
- Visibility: 3/4 of the sky,
  majority of the Galactic Plane

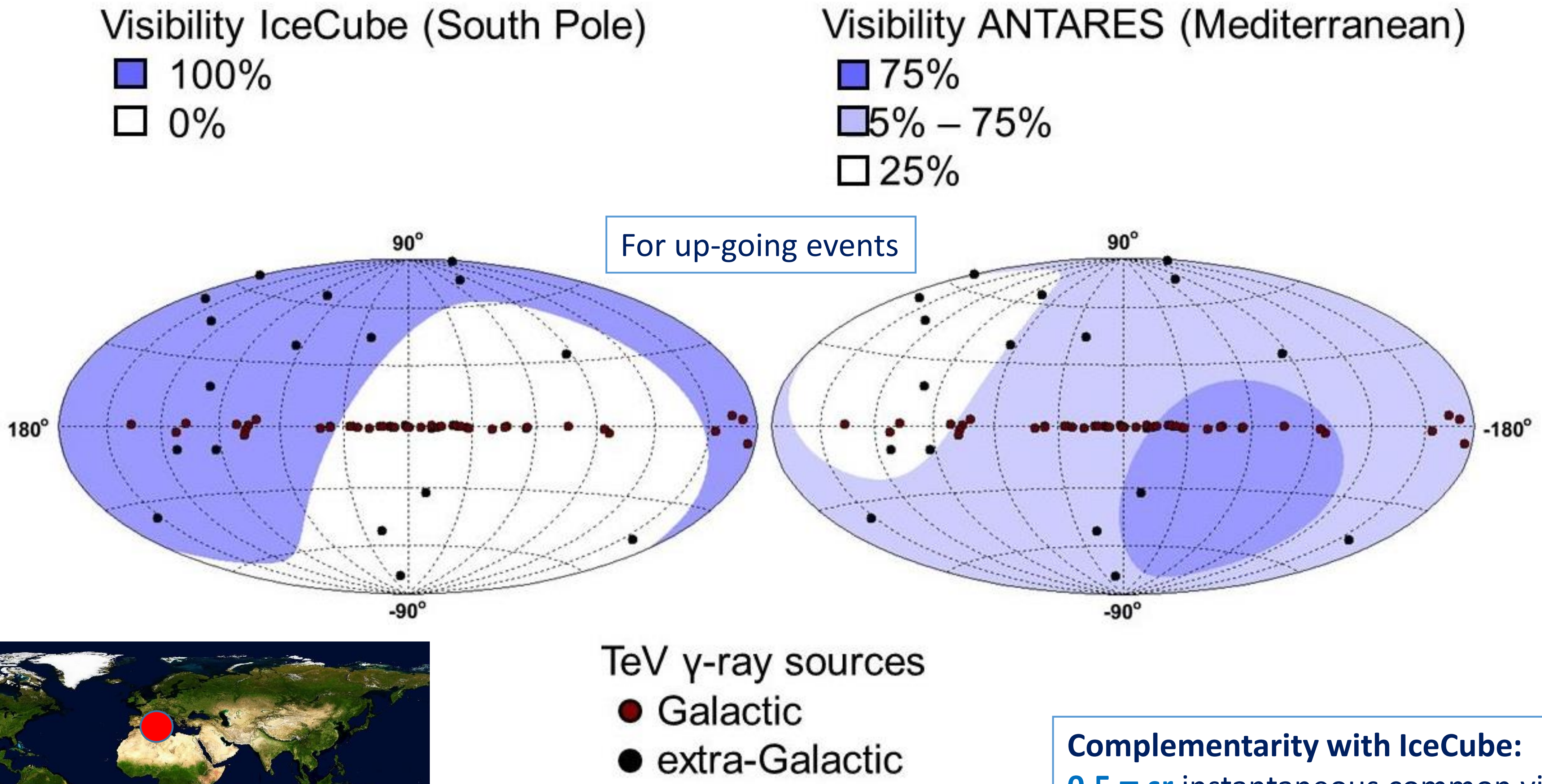
12 detection lines
25 storeys / line
3 PMTs / storey
Total 885 10'' PMTs.



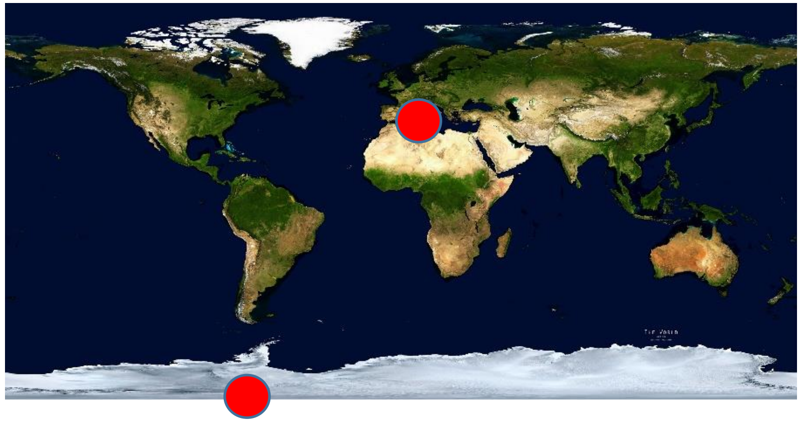
S=0.1 km^2

2475 m depth





For up-going events

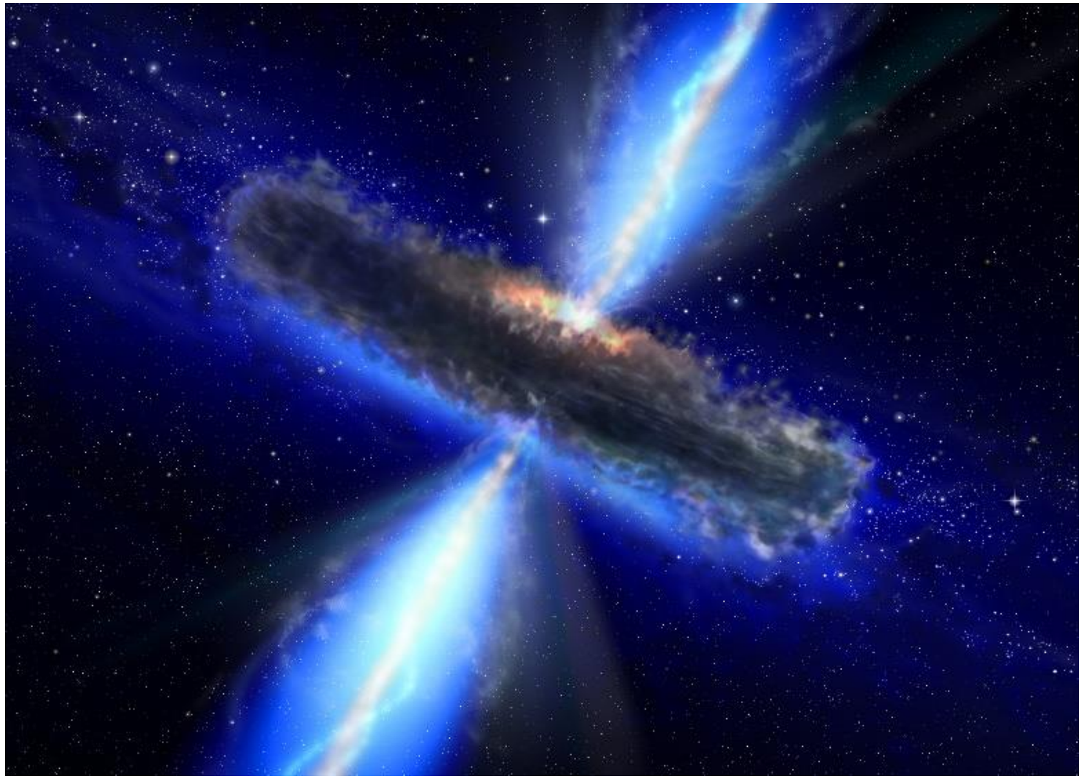


Complementarity with IceCube:
0.5 π sr instantaneous common view
1.5 π sr common view per day

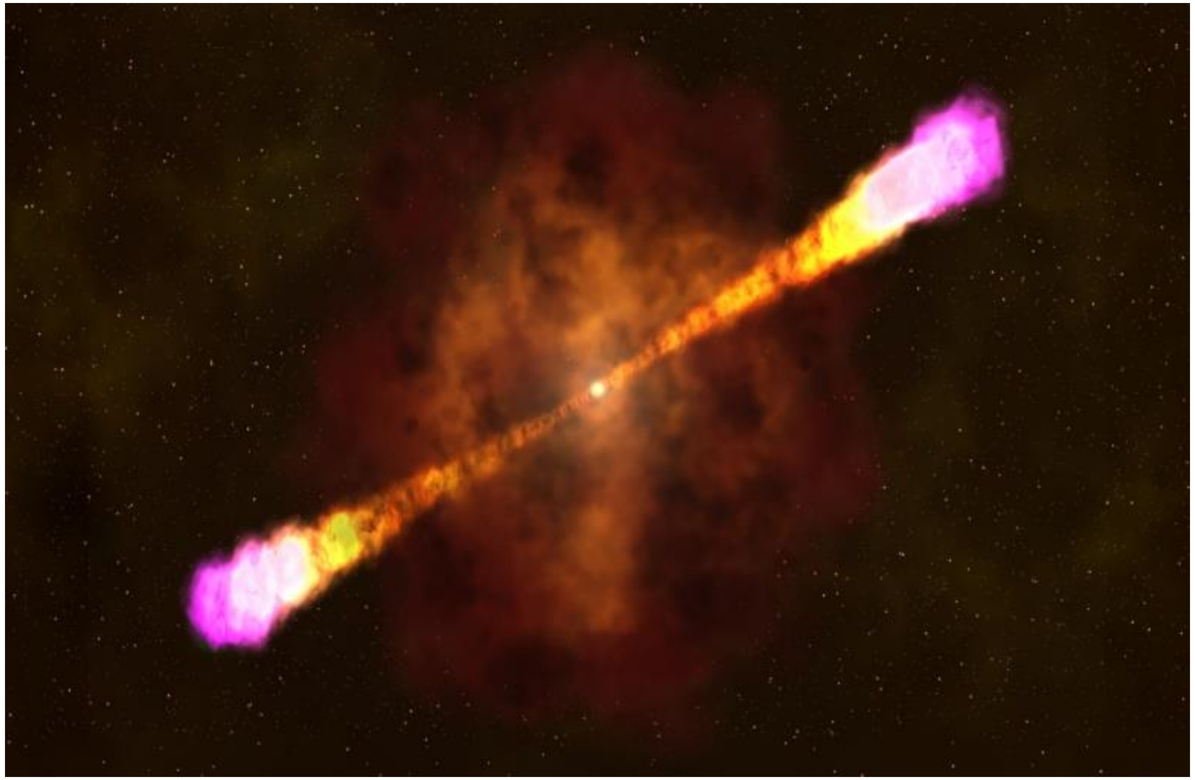
High Energy Neutrino Sources

- **Galactic:**
  Supernova remnants, Microquasars, ...
- **Extragalactic:**
  AGNs, GRBs, ...

AGN

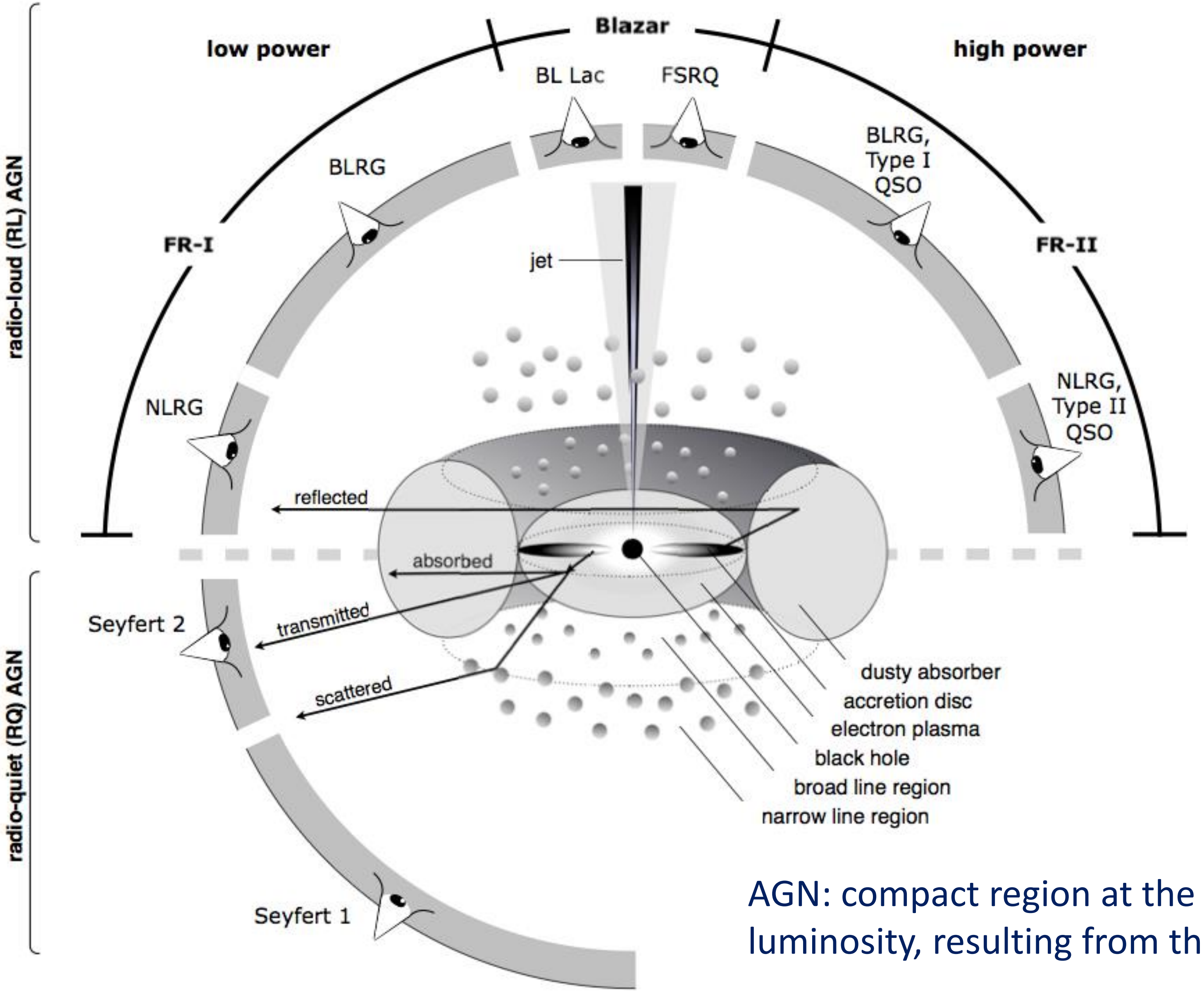


GRB



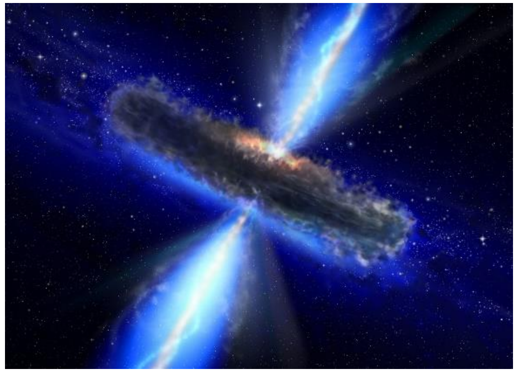
*Artist's impressions

AGN family



The VHE extragalactic sky is dominated by emission from blazars, a class of non-thermal jet-powered AGN known as radio-loud AGN.

- Most galaxies contain at least one SMBH.
- Light generated by friction between the falling dust grains outshines the entire host galaxy (called active galaxy).



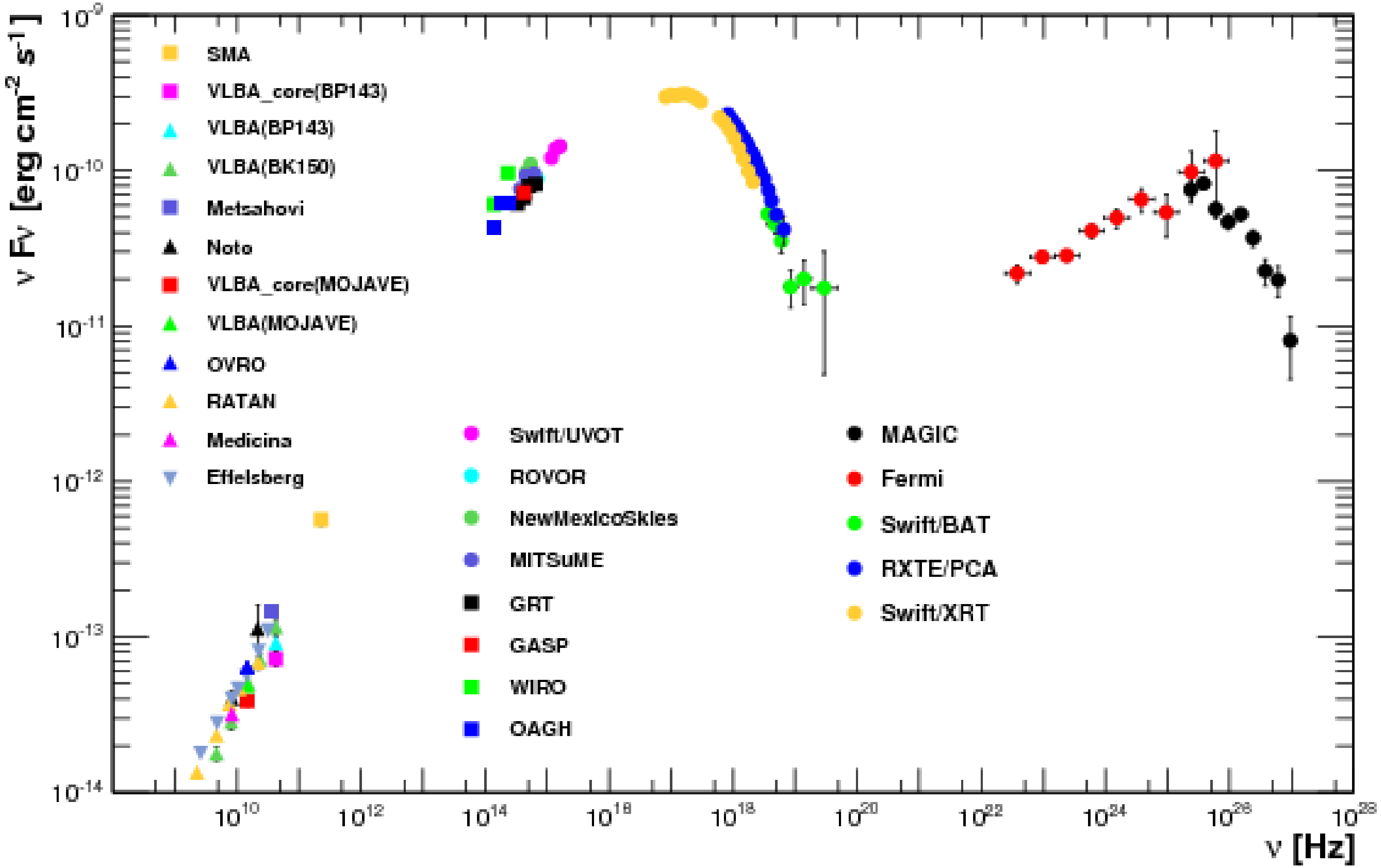
AGN: compact region at the center of a galaxy with very high luminosity, resulting from the accretion of matter by an SMBH

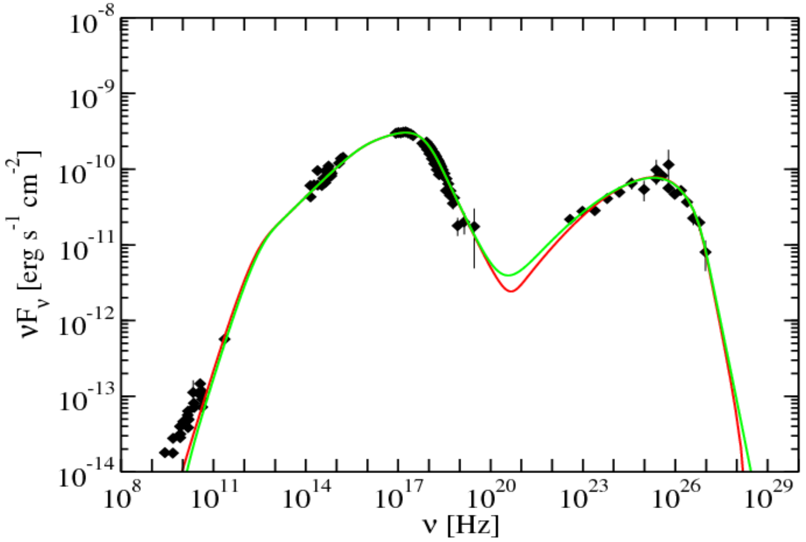
The Spectral Energy Distribution (SED) of blazars with **2 components**:

- **Low - energy** from radio to X-rays : *-> assumed to come from synchrotron emission.*
- **High- energy** from X-rays to TeV : *-> the origin is still under discussion: from IC in the leptonic processes.*

  Some hadronic scenarios introduce relativistic protons to explain the HE bump generally seen in the MeV to TeV range for BL Lac objects.

Both leptonic and hadronic models can generally fit blazar SEDs well. Possible distinguishing diagnostics -> **Neutrinos**





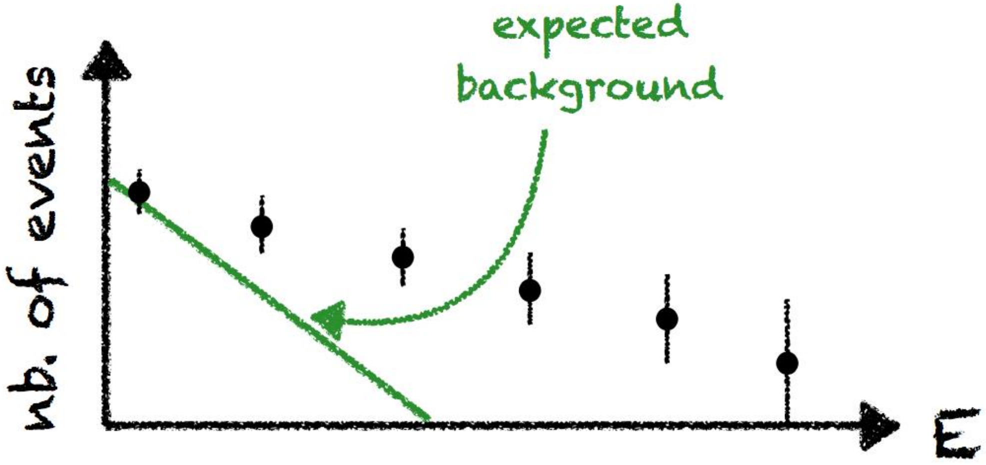
Ex: SED of Mrk 421 over all the observations during the multifrequency campaign in 2009.

Looking for excess at high energies:

➜ diffuse flux analyses

Concerns mainly extragalactic sources

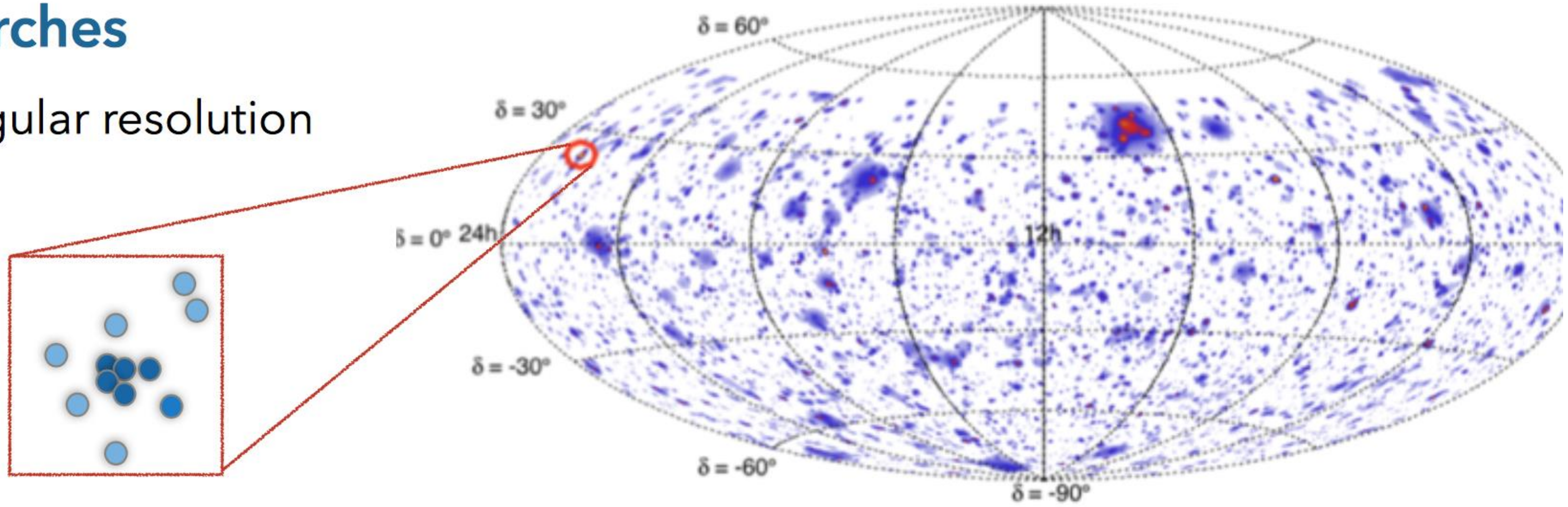
Requires good energy resolution



Looking for anisotropies (clusters of events) in the sky:

➜ point source searches

Requires good angular resolution



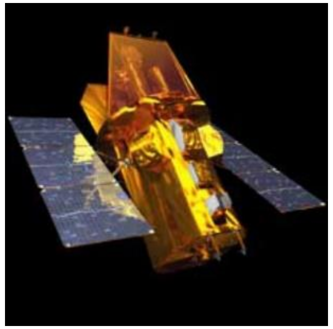
Looking for coincidences with other astrophysical signals:

➜ multi-messenger searches

Requires temporal coincidences with other probes (CR, GW, photons)

Multimessenger Astronomy

Look for neutrinos in coincidence with signals detected by HAWC (time+space correlation



X-rays

Swift

γ-rays

Fermi, HAWC, MAGIC, H.E.S.S, VERITAS

IR, VIS, UV

ZADKO, TAROT, MASTER

High Energy Neutrinos

UHECR

Auger

SUPERB-Parkes, MWA

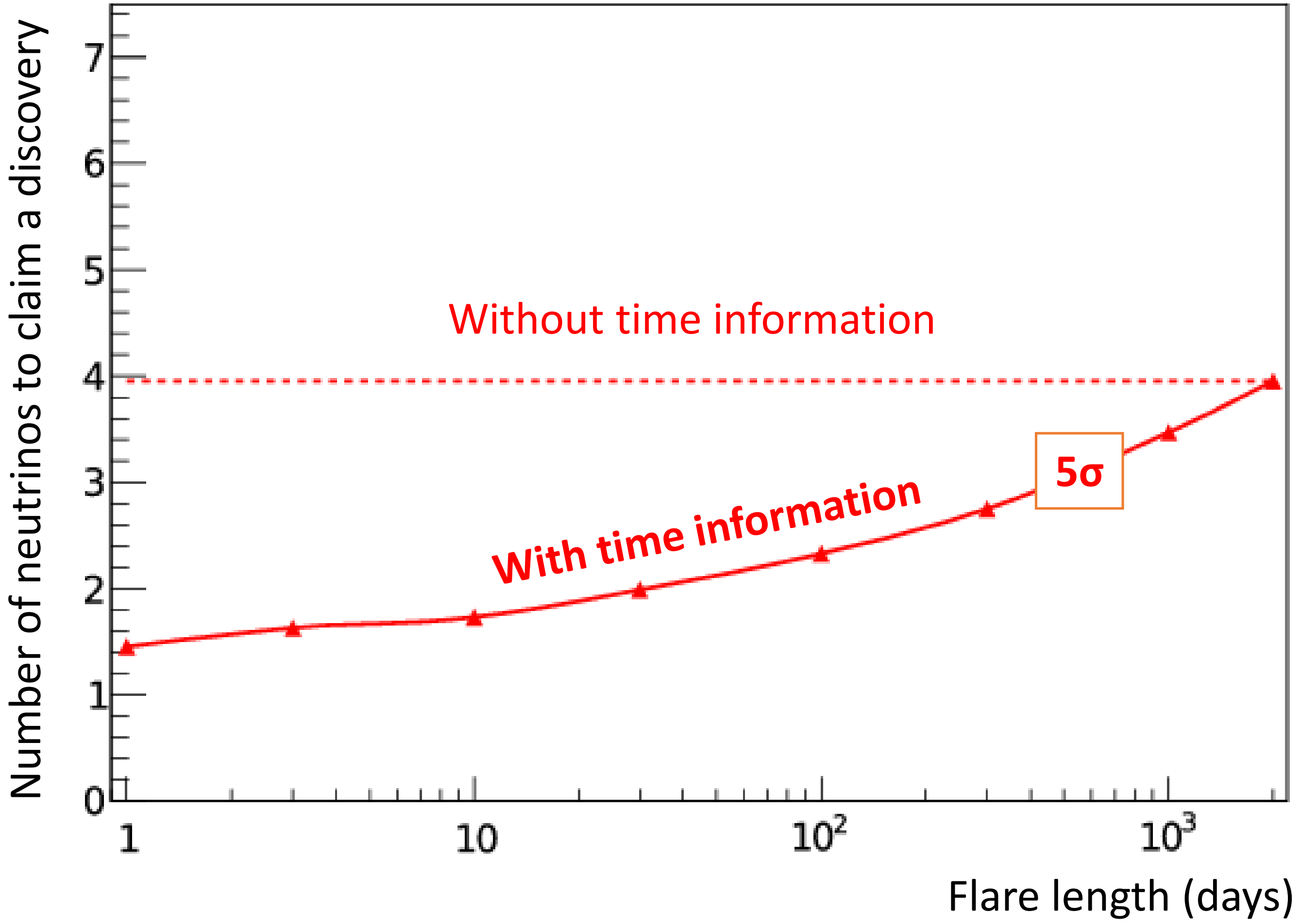
Radio

IPHC/APC

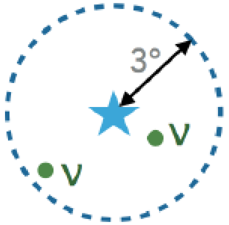
LIGO, VIRGO

GW

Principle of Time-dependent analysis



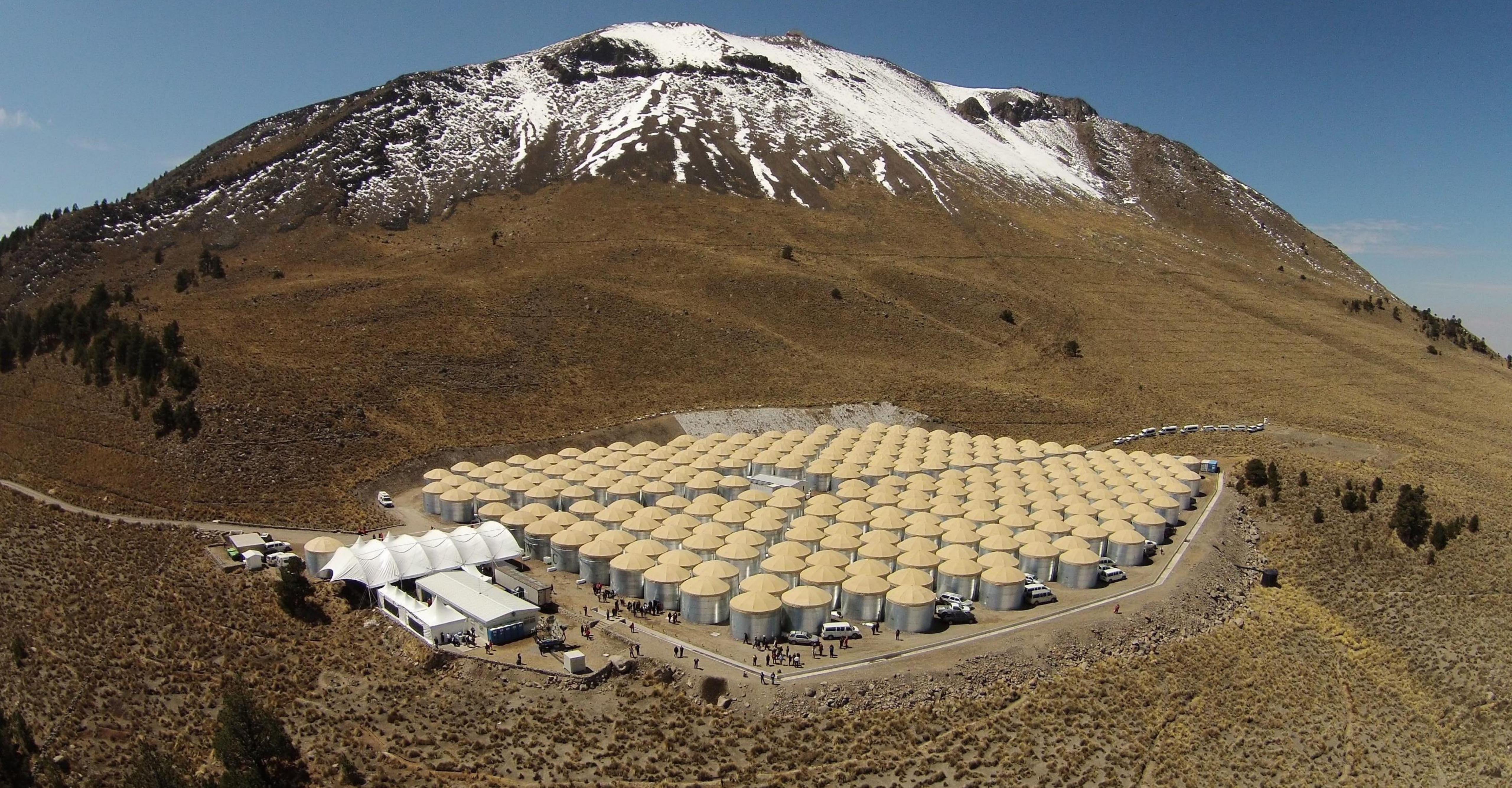
Average number of events required for a 5σ discovery (50% probability) in 3^0, for sources at $\delta=-40^0$ and with E^{-2} energy spectrum.



Number of events required for a discovery is lower and lower when the flare width is reduced.

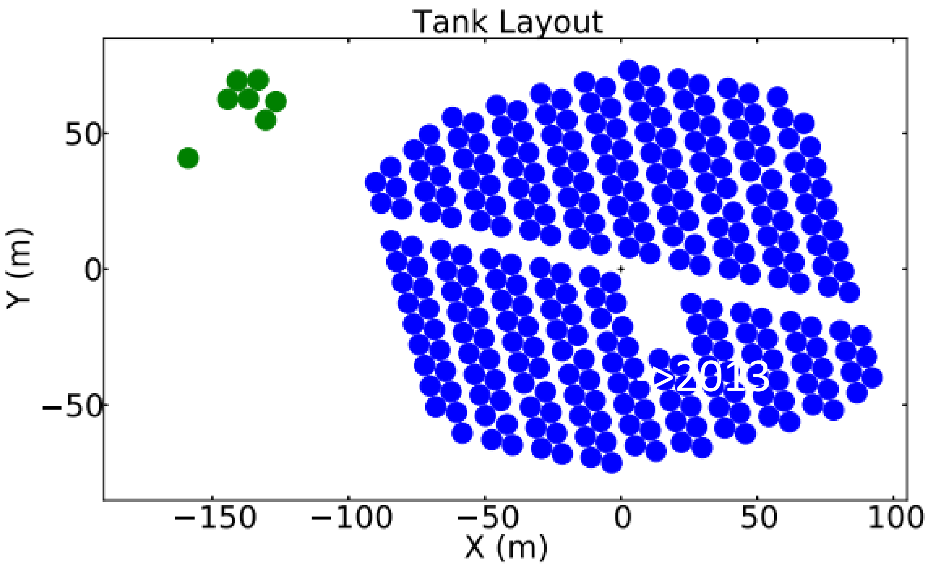
Implementation of time dependent analysis reduce the amount of signal required to claim a discovery by a factor of 2 or more and improves the discovery power, especially for shorter flares.

The High Altitude Water Cherenkov (HAWC)

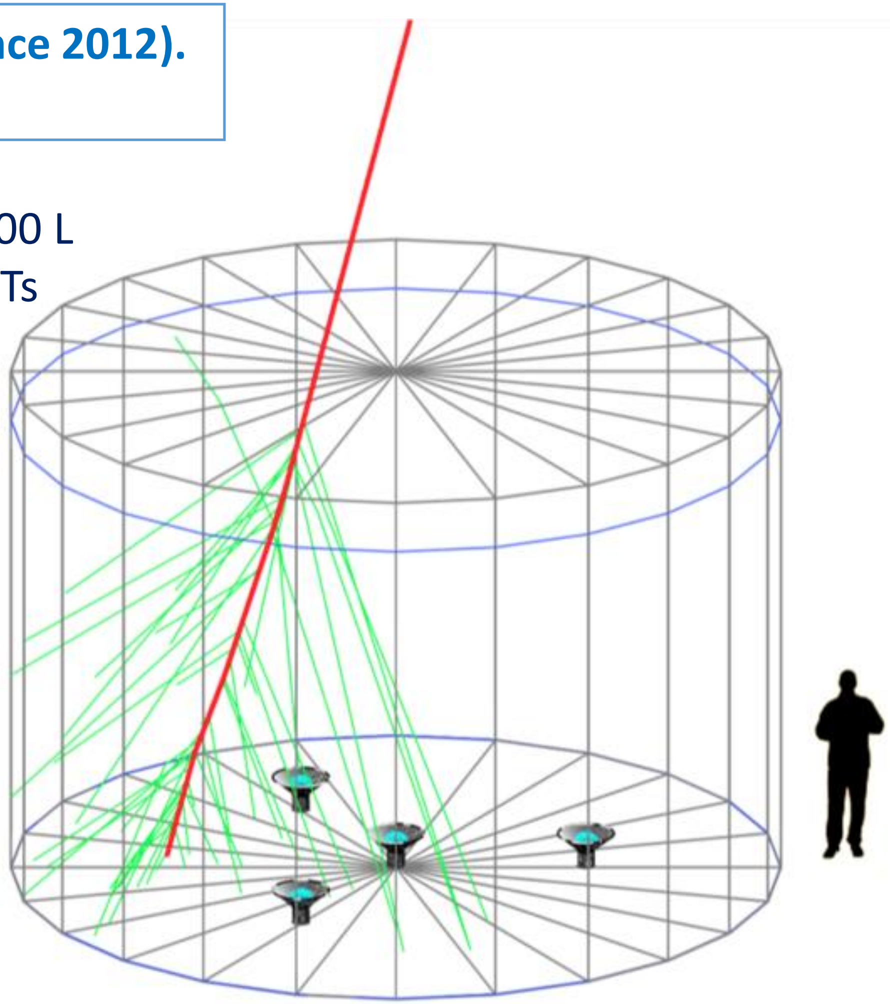


The High Altitude Water Cherenkov (HAWC)

HAWC-300 fully operational began operation on March 20, 2015 (partially since 2012). Currently the most sensitive wide-field-of-view TeV gamma-ray observatory.



300 tanks (WCDs) with 200 000 L of ultra-pure water and 4 PMTs on total S = 22 000 m²



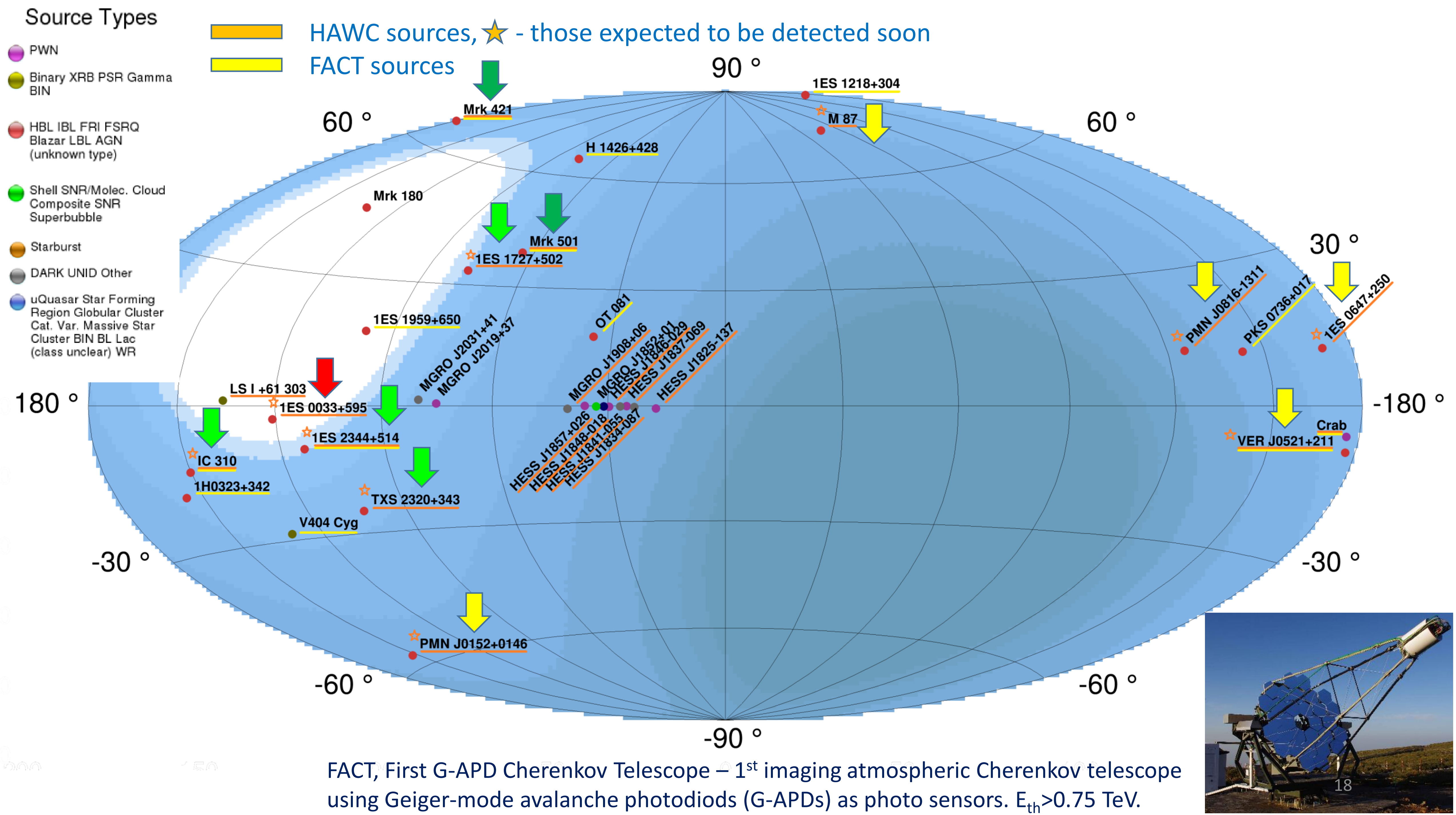
HAWC in numbers:

- **Energy range: 100 GeV - 100 TeV**
- **FOV: 1/6 of sky => scans 2/3 of all sky (4π) daily.**
- **Angular resolution: <0.5° (for E>1 TeV)**
- **Most sensitive to sources with δ: (-26^0;$+64^0$)**

Such capabilities make unprecedented TeV light curve data available for studying flaring behavior of blazars.

🟧 HAWC sources, ☆ - those expected to be detected soon

🟨 FACT sources



FACT, First G-APD Cherenkov Telescope – 1st imaging atmospheric Cherenkov telescope using Geiger-mode avalanche photodiods (G-APDs) as photo sensors. E_{th}>0.75 TeV.

Time dependent analysis: HAWC blazars

First official Light curves (LC) released

Light curve is a graph of light intensity as a function of time

“DAILY MONITORING OF TEV GAMMA-RAY EMISSION FROM MRK 421, MRK 501, AND THE CRAB NEBULA WITH HAWC”

First 17 months of data from the HAWC Observatory!

- **Markarian 421 (Mrk 421)**
- **Markarian 501 (Mrk 501)**

➡ **found clear variability** on time scales of one day

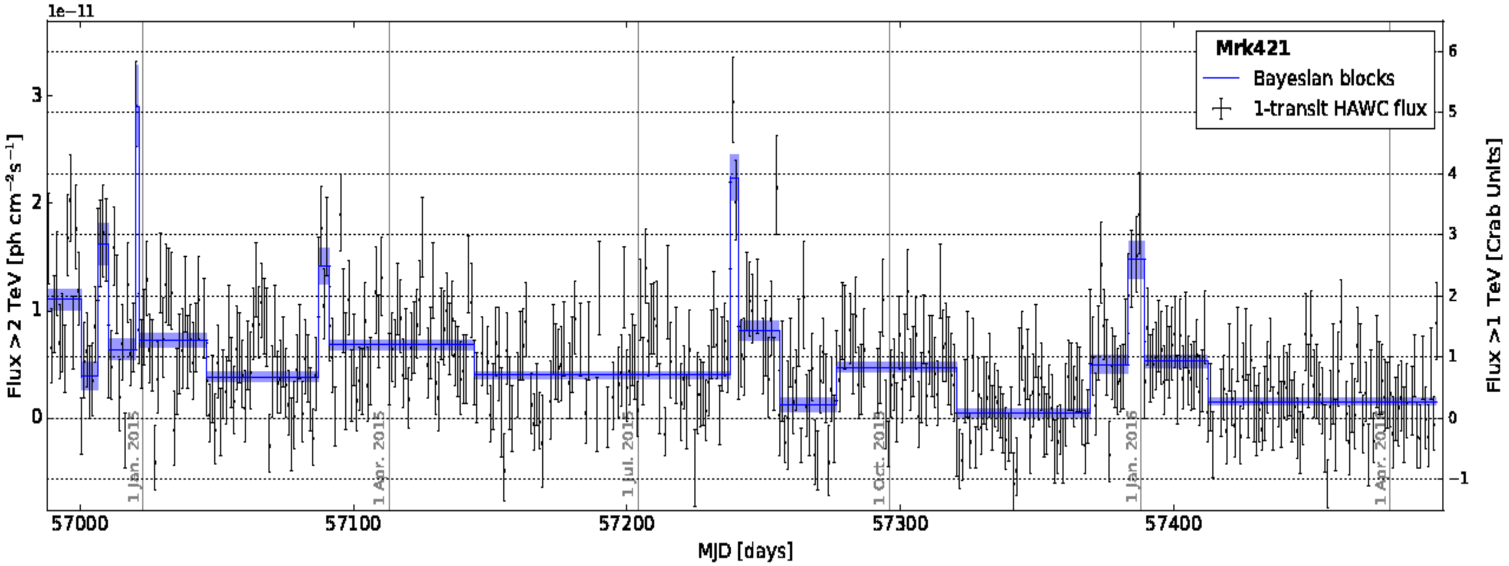
MJD: 56988 – 57497
Date: 27/11/2014 – 19/04/2016

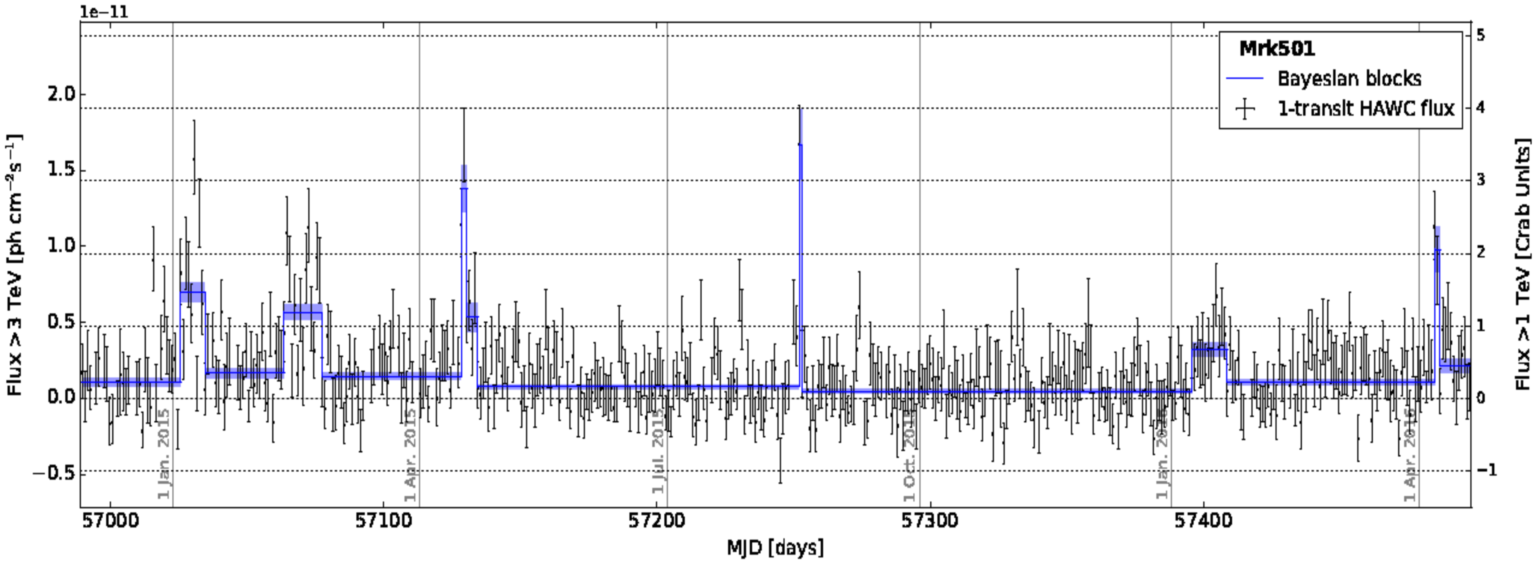
Mrk 421 and Mrk 501 are the brightest and closest BL Lac objects known!
dL = 134 Mpc, z = 0.031 and dL = 143 Mpc, z=0.033 respectively

As the nearest blazars to Earth, both are excellent sources to test the blazar-neutrino connection scenario, especially during flares where time-dependent neutrino searches have a higher detection probability.

The shape of the signal is extracted directly for the γ-ray LC assuming the proportionality between γ-ray and ν fluxes

Light curves for HAWC AGNs





Flux LCs time range: 2014 Nov 26 - 2016 Apr 20

The integrated fluxes are derived from fitting F_i in

$$dN/dE = F_i \, (E/(1\ \mathrm{TeV}))^{-\gamma} \ \exp(-E/(E0))$$

E0 = 5 TeV, γ=2.2 for Mrk 421
E0 = 6 TeV, γ=1.6 for Mrk 501

Conversion to CU units via dividing by the HAWC measurement of the average Crab Nebula γ-ray flux.

The blue lines show the distinct flux states.

HAWC flares

HAWC identified 19 and 14 distinct fluxes for Mrk 421 and Mrk 501 relatively (Bayesian blocks have been done).

HAWC monitor sources up to 6 hours per day.
= > Existed gaps is with duration <1 day
= > Can be used as a 1 day binned flare.

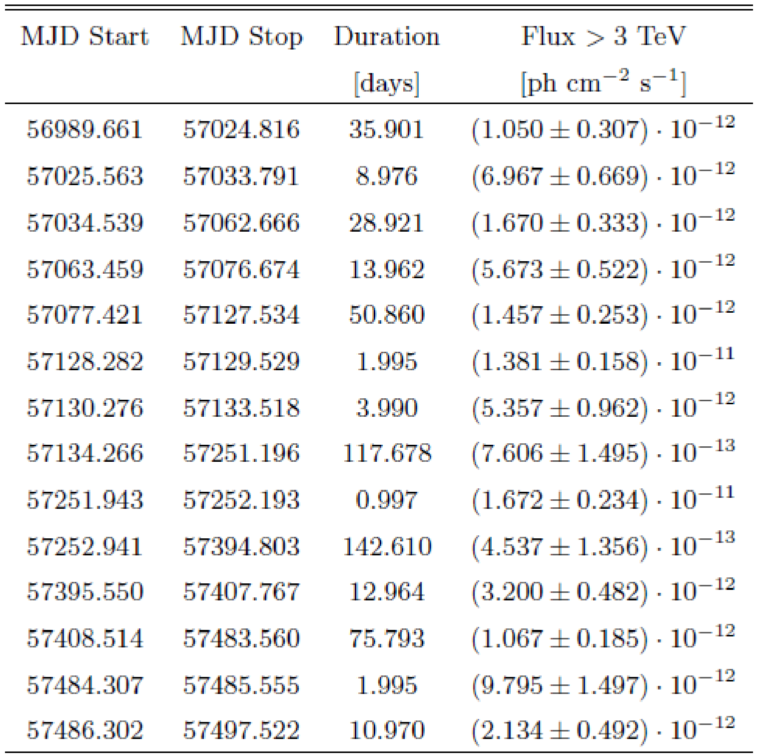


Table 3. HAWC Bayesian blocks for Mrk 501

MJD Start	MJD Stop	Duration [days]	Flux > 3 TeV [ph cm^{-2} s^{-1}]
56989.661	57024.816	35.901	$(1.050 \pm 0.307) \cdot 10^{-12}$
57025.563	57033.791	8.976	$(6.967 \pm 0.669) \cdot 10^{-12}$
57034.539	57062.666	28.921	$(1.670 \pm 0.333) \cdot 10^{-12}$
57063.459	57076.674	13.962	$(5.673 \pm 0.522) \cdot 10^{-12}$
57077.421	57127.534	50.860	$(1.457 \pm 0.253) \cdot 10^{-12}$
57128.282	57129.529	1.995	$(1.381 \pm 0.158) \cdot 10^{-11}$
57130.276	57133.518	3.990	$(5.357 \pm 0.962) \cdot 10^{-12}$
57134.266	57251.196	117.678	$(7.606 \pm 1.495) \cdot 10^{-13}$
57251.943	57252.193	0.997	$(1.672 \pm 0.234) \cdot 10^{-11}$
57252.941	57394.803	142.610	$(4.537 \pm 1.356) \cdot 10^{-13}$
57395.550	57407.767	12.964	$(3.200 \pm 0.482) \cdot 10^{-12}$
57408.514	57483.560	75.793	$(1.067 \pm 0.185) \cdot 10^{-12}$
57484.307	57485.555	1.995	$(9.795 \pm 1.497) \cdot 10^{-12}$
57486.302	57497.522	10.970	$(2.134 \pm 0.492) \cdot 10^{-12}$

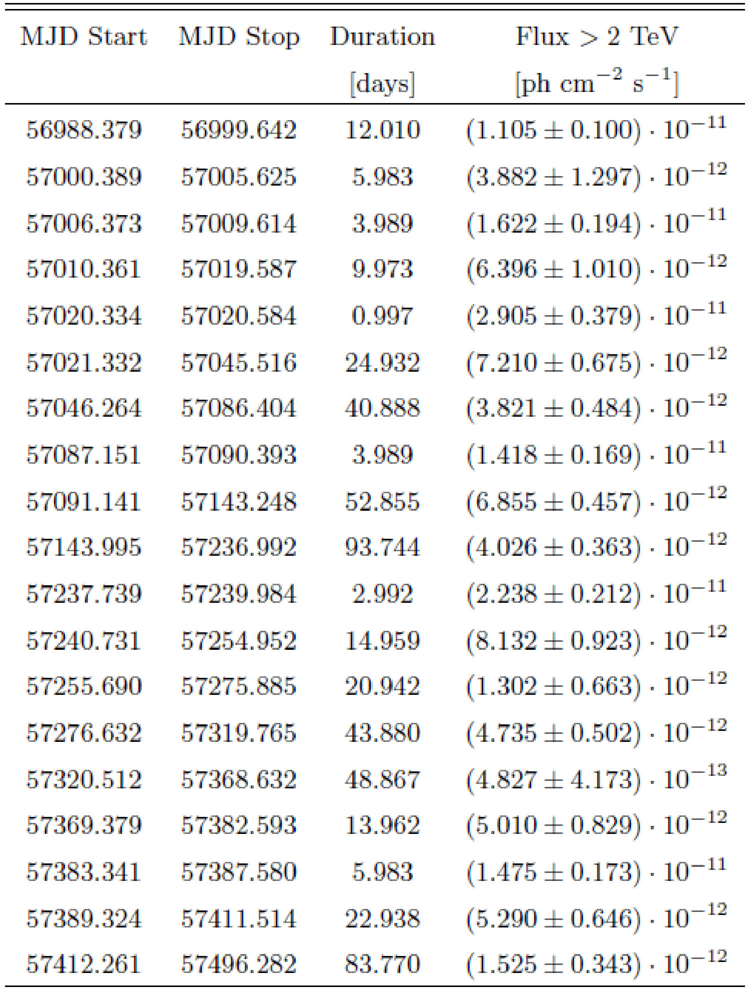
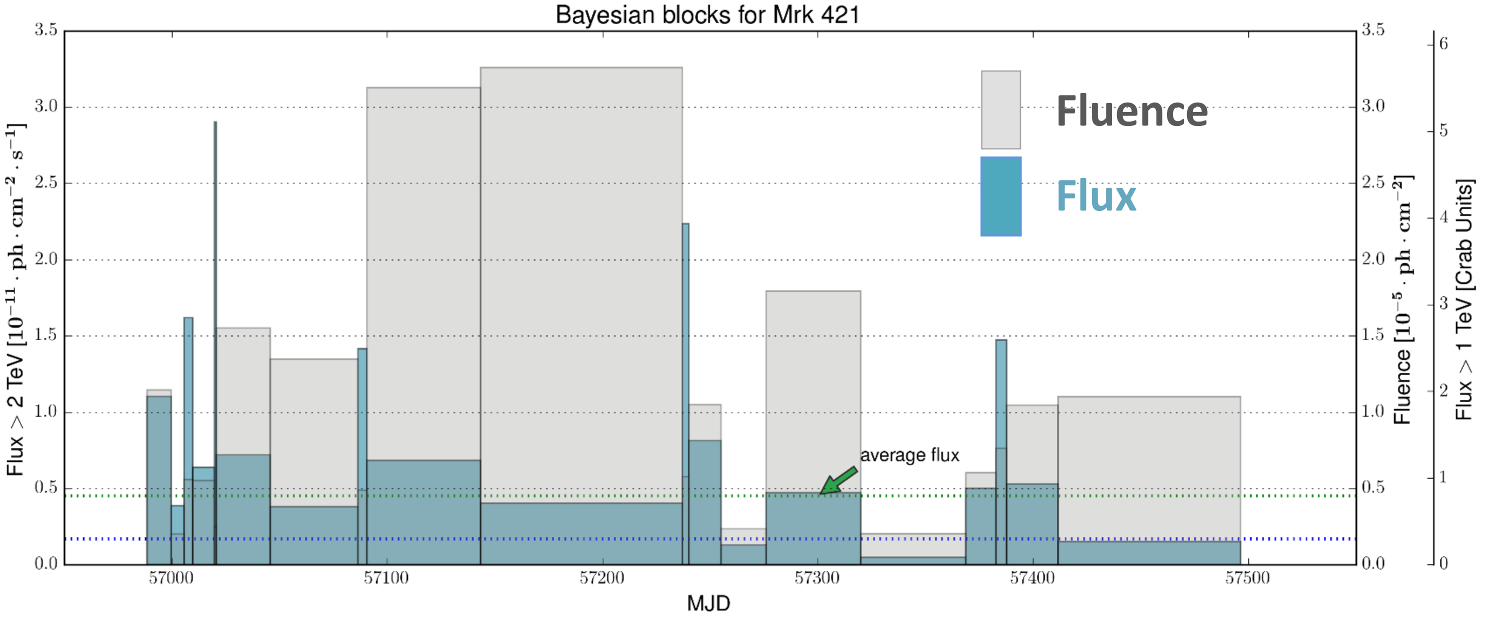
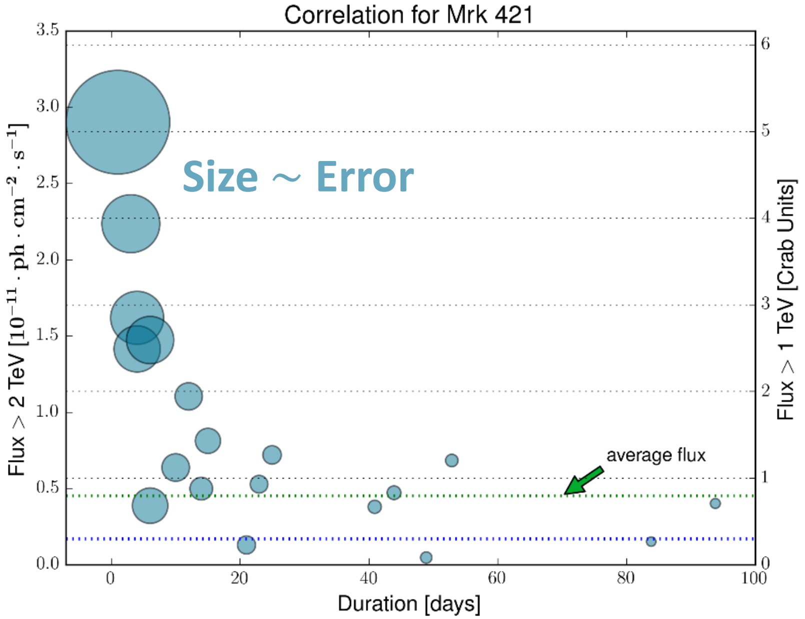


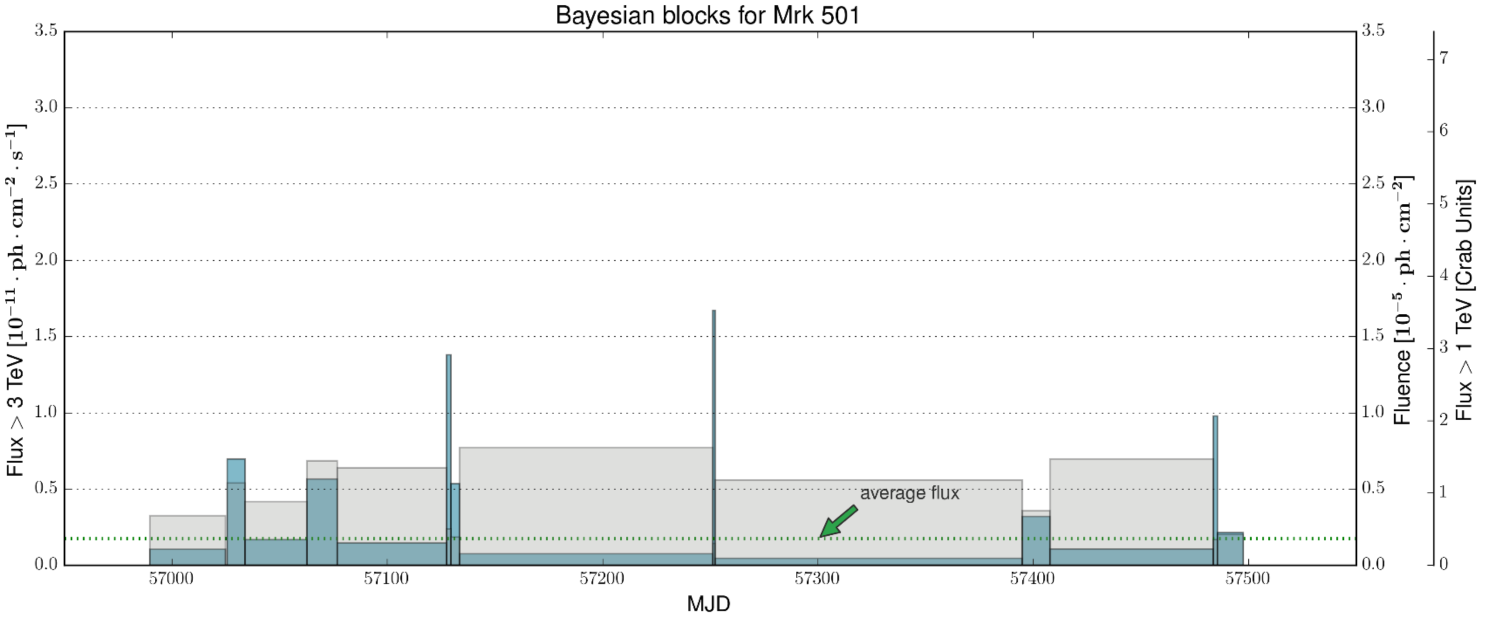
Table 2. HAWC Bayesian blocks for Mrk 421

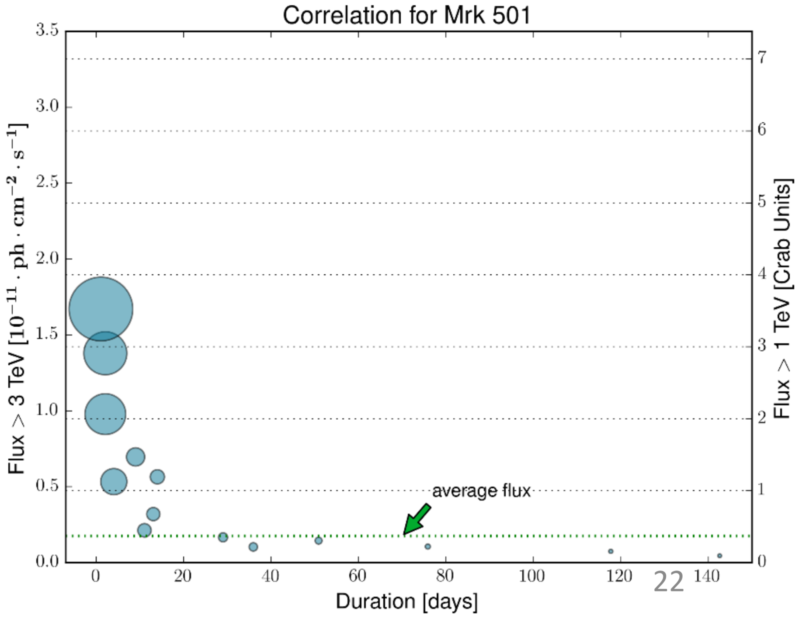
MJD Start	MJD Stop	Duration [days]	Flux > 2 TeV [ph cm^{-2} s^{-1}]
56988.379	56999.642	12.010	$(1.105 \pm 0.100) \cdot 10^{-11}$
57000.389	57005.625	5.983	$(3.882 \pm 1.297) \cdot 10^{-12}$
57006.373	57009.614	3.989	$(1.622 \pm 0.194) \cdot 10^{-11}$
57010.361	57019.587	9.973	$(6.396 \pm 1.010) \cdot 10^{-12}$
57020.334	57020.584	0.997	$(2.905 \pm 0.379) \cdot 10^{-11}$
57021.332	57045.516	24.932	$(7.210 \pm 0.675) \cdot 10^{-12}$
57046.264	57086.404	40.888	$(3.821 \pm 0.484) \cdot 10^{-12}$
57087.151	57090.393	3.989	$(1.418 \pm 0.169) \cdot 10^{-11}$
57091.141	57143.248	52.855	$(6.855 \pm 0.457) \cdot 10^{-12}$
57143.995	57236.992	93.744	$(4.026 \pm 0.363) \cdot 10^{-12}$
57237.739	57239.984	2.992	$(2.238 \pm 0.212) \cdot 10^{-11}$
57240.731	57254.952	14.959	$(8.132 \pm 0.923) \cdot 10^{-12}$
57255.690	57275.885	20.942	$(1.302 \pm 0.663) \cdot 10^{-12}$
57276.632	57319.765	43.880	$(4.735 \pm 0.502) \cdot 10^{-12}$
57320.512	57368.632	48.867	$(4.827 \pm 4.173) \cdot 10^{-13}$
57369.379	57382.593	13.962	$(5.010 \pm 0.829) \cdot 10^{-12}$
57383.341	57387.580	5.983	$(1.475 \pm 0.173) \cdot 10^{-11}$
57389.324	57411.514	22.938	$(5.290 \pm 0.646) \cdot 10^{-12}$
57412.261	57496.282	83.770	$(1.525 \pm 0.343) \cdot 10^{-12}$


Bayesian blocks for Mrk 421


Correlation for Mrk 421

Average fluxes: ~0.8 CU for Mrk 421 (higher than previous estimates for an upper limit to the baseline flux ~0.3 CU) and ~0.3 CU for Mrk 501


Bayesian blocks for Mrk 501


Correlation for Mrk 501

Time dependent analysis

Search for time correlation between neutrino and gamma flares from blazars Mrk 421 and Mrk 501 visible by HAWC.

Time information from the sources

- improves the analysis by reduce of background
- improves the discovery potential over a time integrated search.

→ The LC can be used as a time Probability Distribution Function (PDF)

The data is parameterized as a 2 components mixture of Signal and Background.

$$\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

The goal is to determine the relative contribution of each component at a given point in the sky at a given time.

→ Calculate the probability to have a signal above a given background model.

Likelihood of the data given n_s is then the product of all the event probability densities:

$$L(n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right]$$

Extended Maximum Likelihood

$$\ln L = \sum_{i=1}^{N} \ln[N_s \cdot P_s(x) + N_b \cdot P_b(x)] - [N_s + N_b]$$

Likelihood: **spatial**, **time** and **energy** terms

Signal term: $P_s(x) = P_s(\alpha) \cdot P_b(E) \cdot P_s(t + lag)$

Background term: $P_b(x) = P_b(\sin\delta) \cdot P_b(E) \cdot P_b(t)$

Test statistics: likelihood ratio analysis

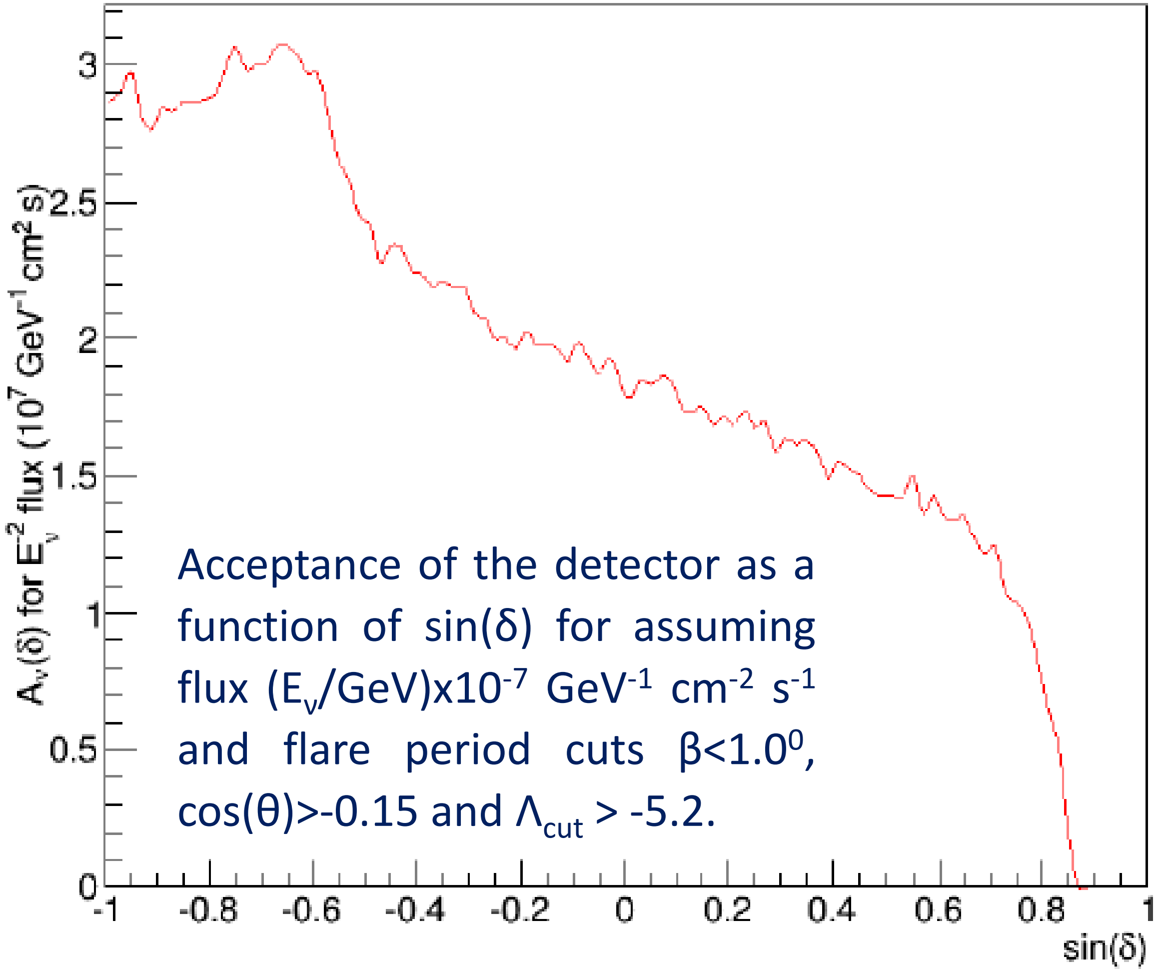
$$TS = log\left[\frac{L(n_s)}{L(n_s = 0)}\right] = \sum_{i=1}^{N} log\left[\frac{\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i}{B_i}\right]$$

used to differentiate between the data and the background.

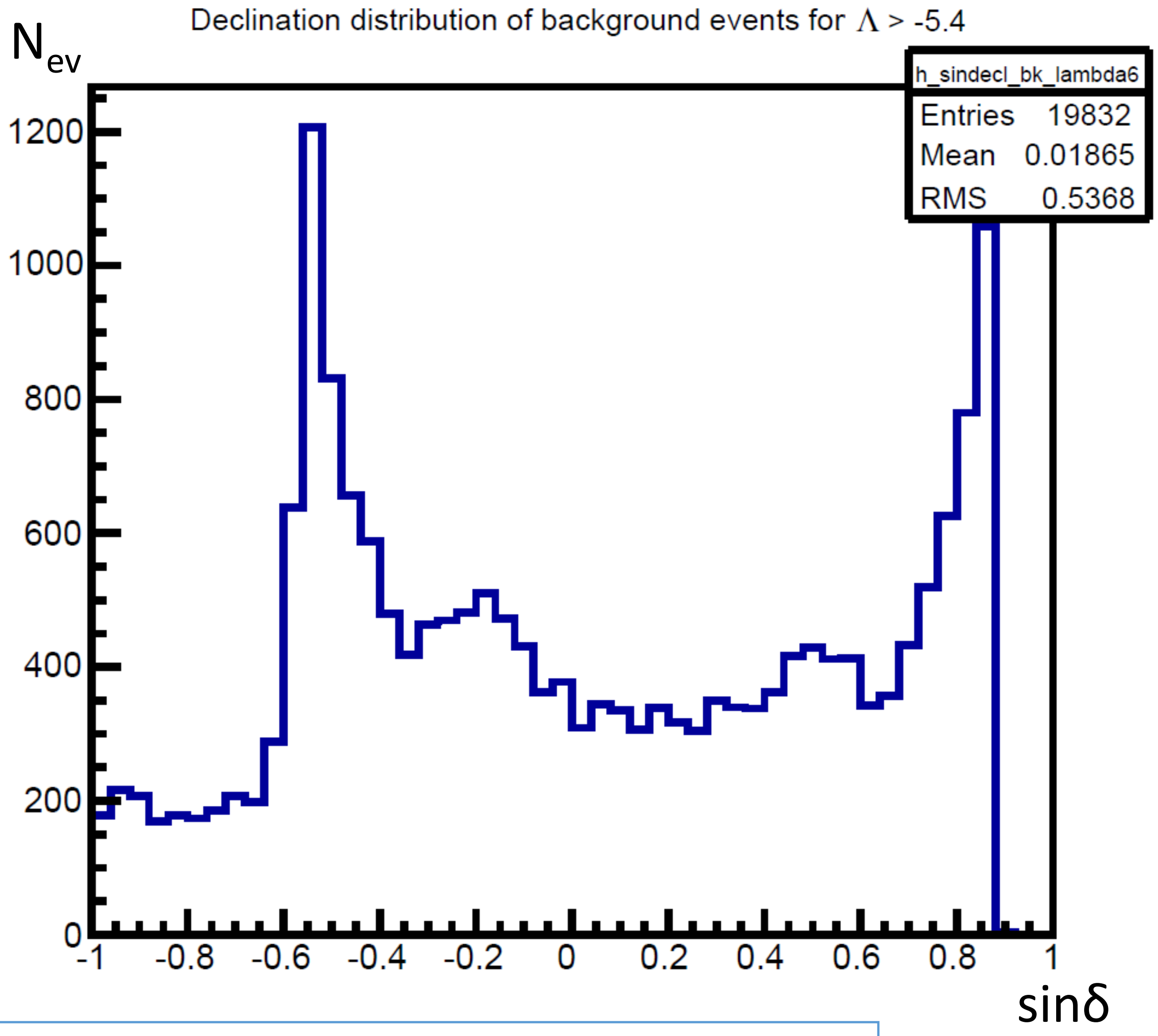
Ratio of the probability for sig+bkg over the probability of only bkg

Spatial

$P_b(\sin\delta)$, Background Angular Distribution



Acceptance of the detector as a function of sin(δ) for assuming flux $(E_\nu/\mathrm{GeV})\times10^{-7}$ GeV^{-1} cm^{-2} s^{-1} and flare period cuts $\beta<1.0^0$, $\cos(\theta)>-0.15$ and $\Lambda_{cut} > -5.2$.



Declination distribution of background events for $\Lambda > -5.4$

Depend on the quality parameter, energy, so computed for each quality parameter and spectrum

$P_s(E)$

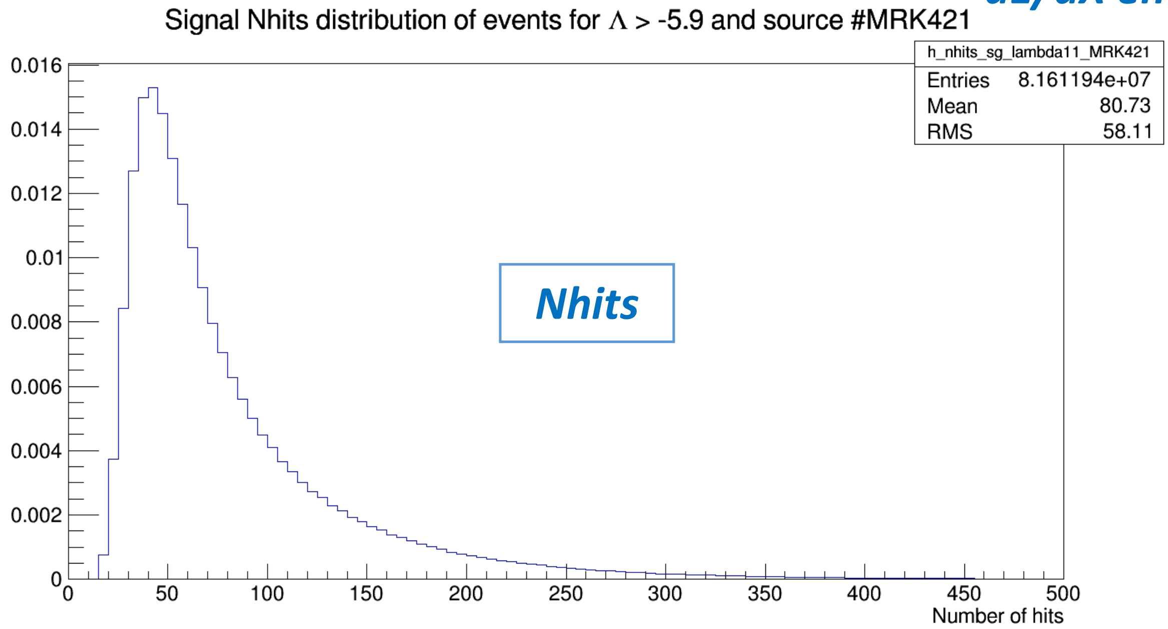
Energy

$P_b(E)$

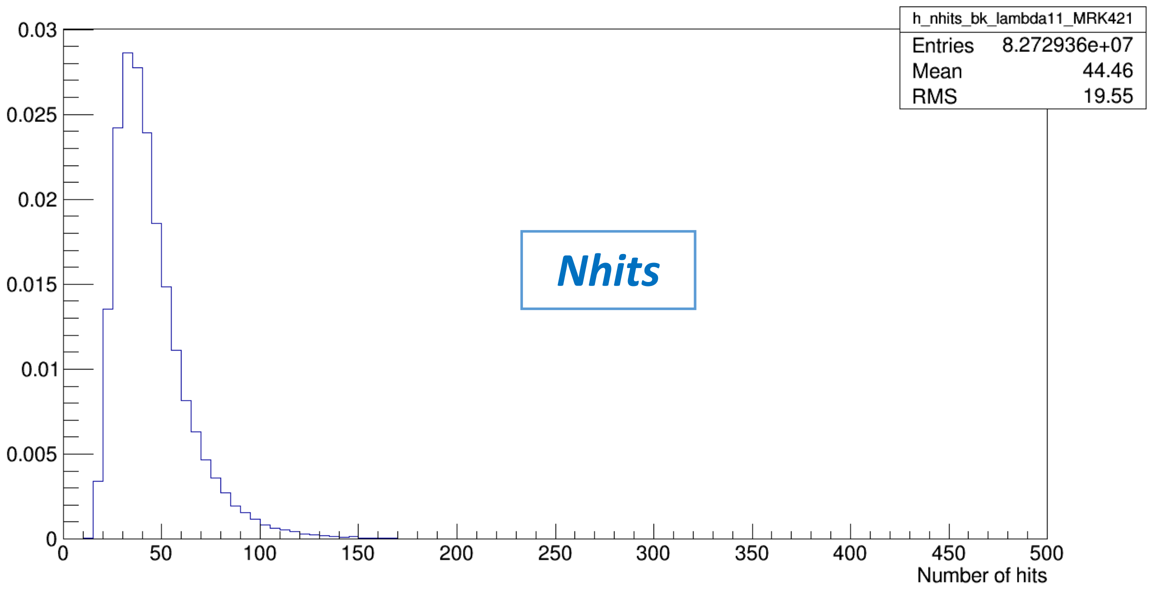
dE/dX energy estimator

or

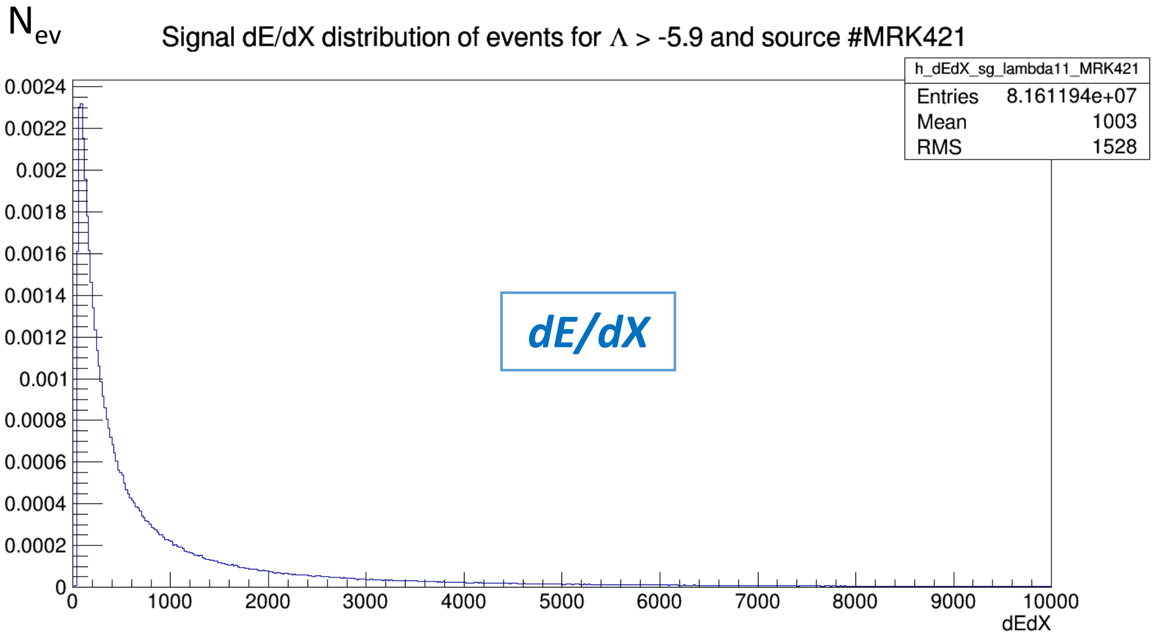
Nhits


Signal Nhits distribution of events for $\Lambda > -5.9$ and source #MRK421

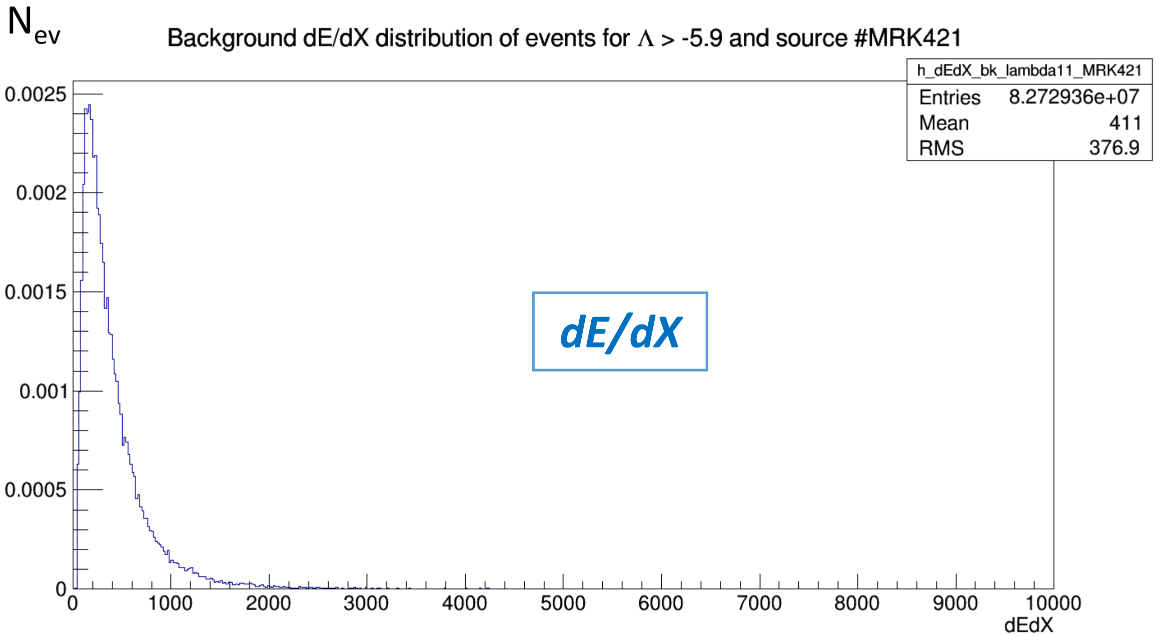
Nhits


Background Nhits distribution of events for $\Lambda > -5.9$ and source #MRK421

Nhits


Signal dE/dX distribution of events for $\Lambda > -5.9$ and source #MRK421

dE/dX

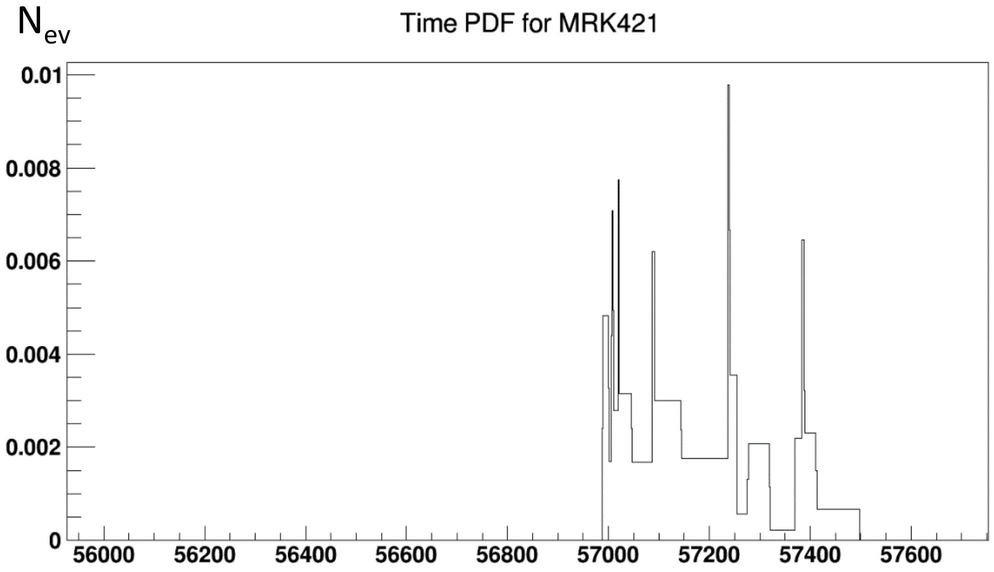

Background dE/dX distribution of events for $\Lambda > -5.9$ and source #MRK421

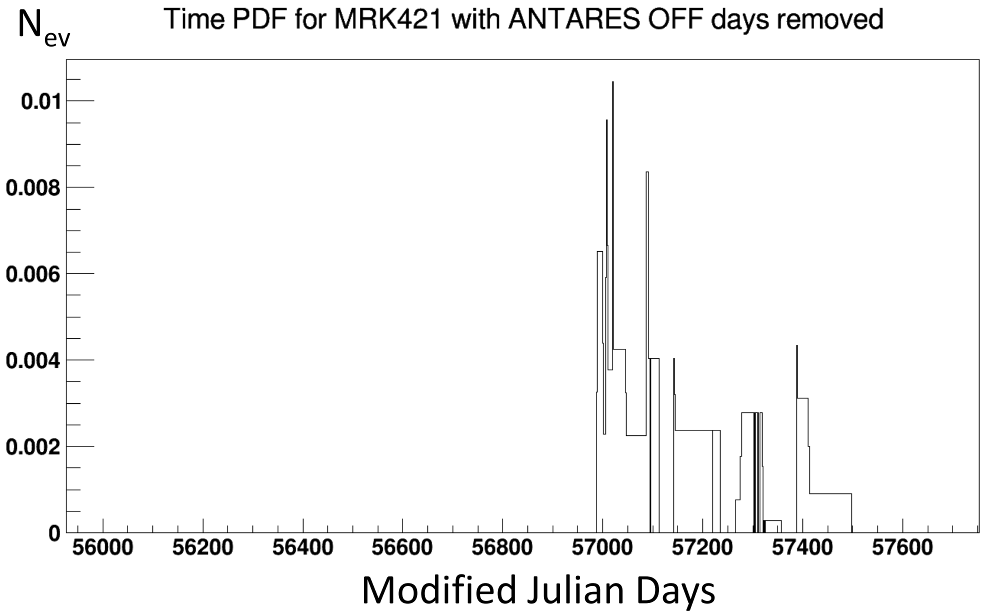
dE/dX

Time

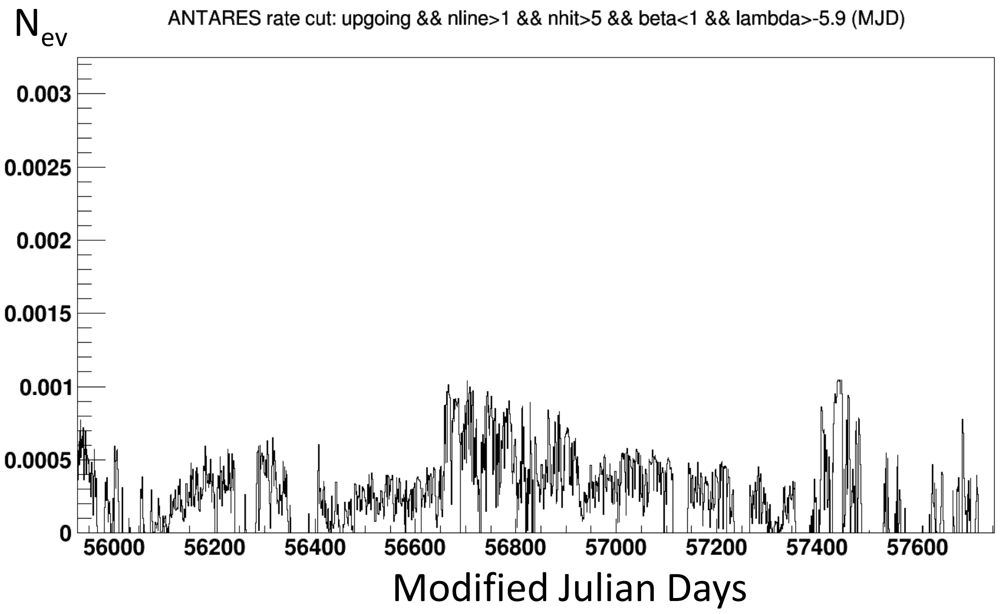
P_s(t+lag), Signal time information

allowed a lag of ±5 days between γ and ν signal





P_b(t), Background Time Distribution

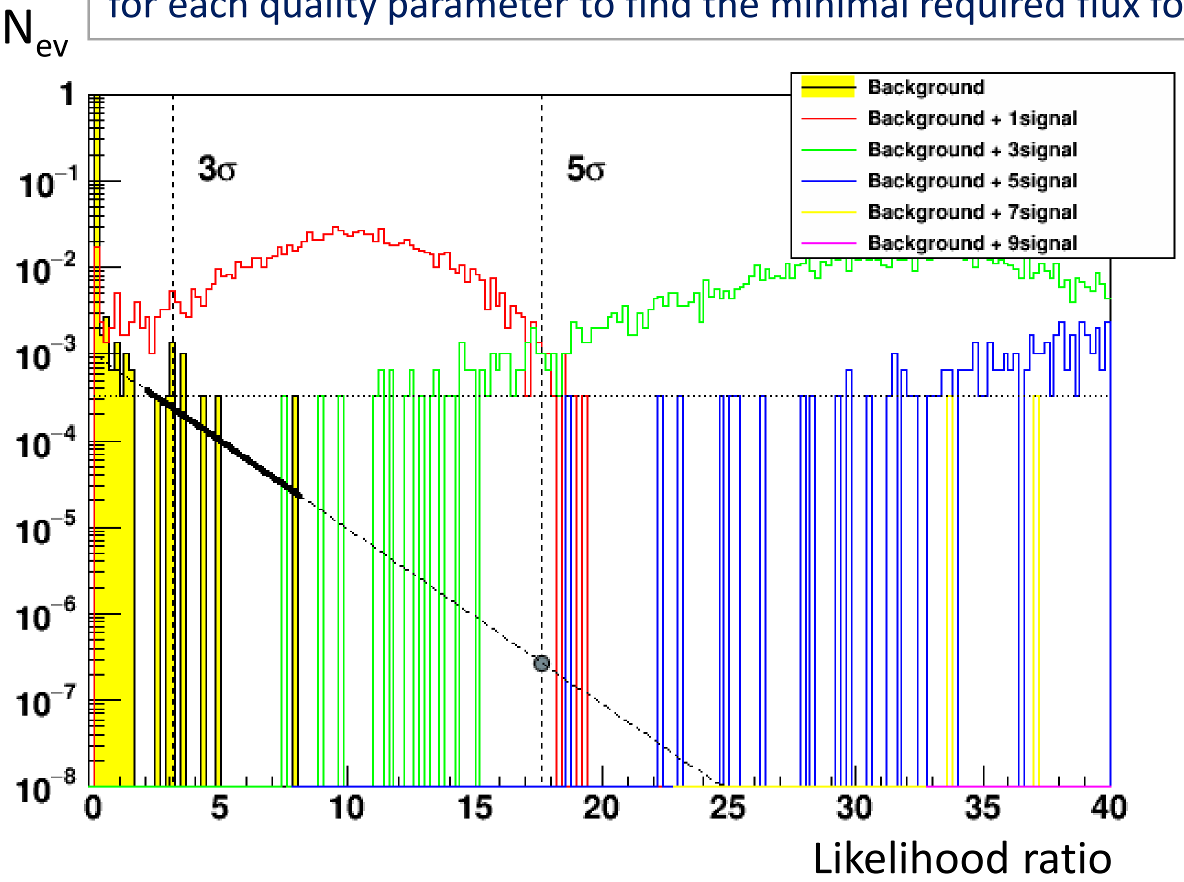


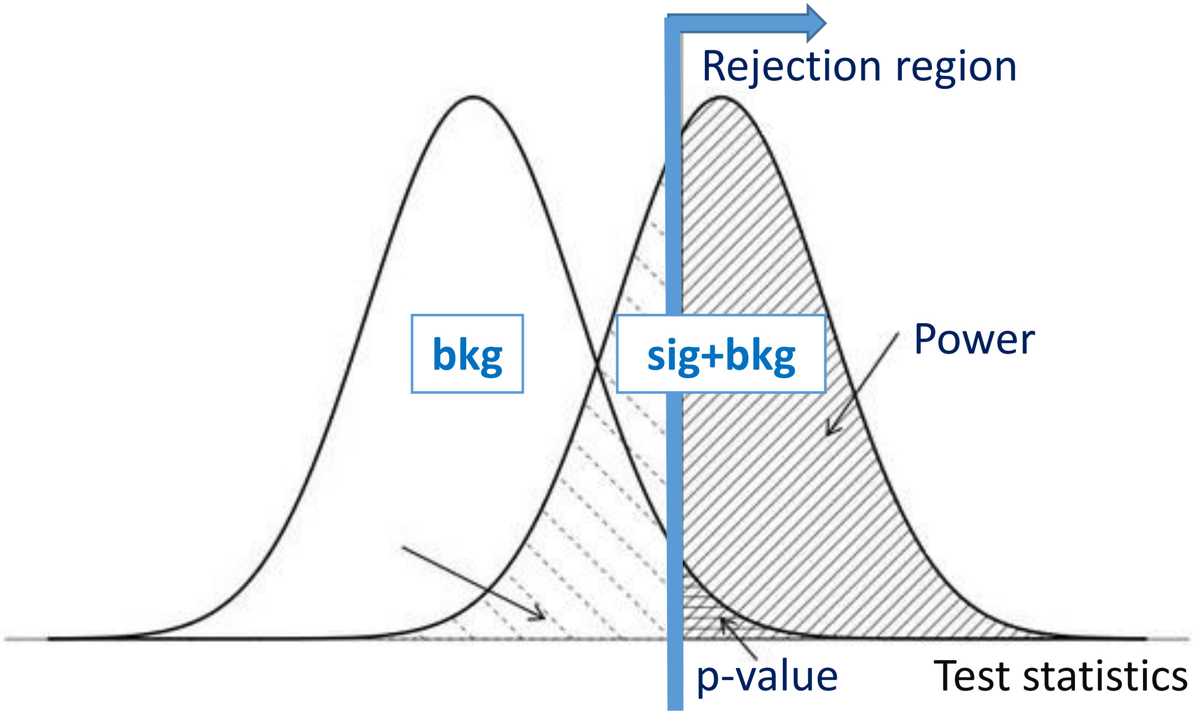
Test statistics *likelihood ratio analysis, $TS=\log(L_{sig+bkg}) - \log(L_{bkg})$*

- The test statistics TS is evaluated by generating pseudo-experiments (PEX) simulating background and signal around the considered source according to sig+bkg and bkg only case.
- The obtained value of TS for the data is compared to the value obtained by PEX.
- Large TS values reject bkg only presense with confident level equal to the fraction of the distribution above the obtained TS.
- Discovery potential $DP^{5\sigma}$ - average number of signal events N_s required to achieve p-value lower than $5.7\cdot10^{-7}$ for 5σ discovery.

Depend on the quality parameter, next is optimization and DP calculation for each quality parameter to find the minimal required flux for 5σ discovery.

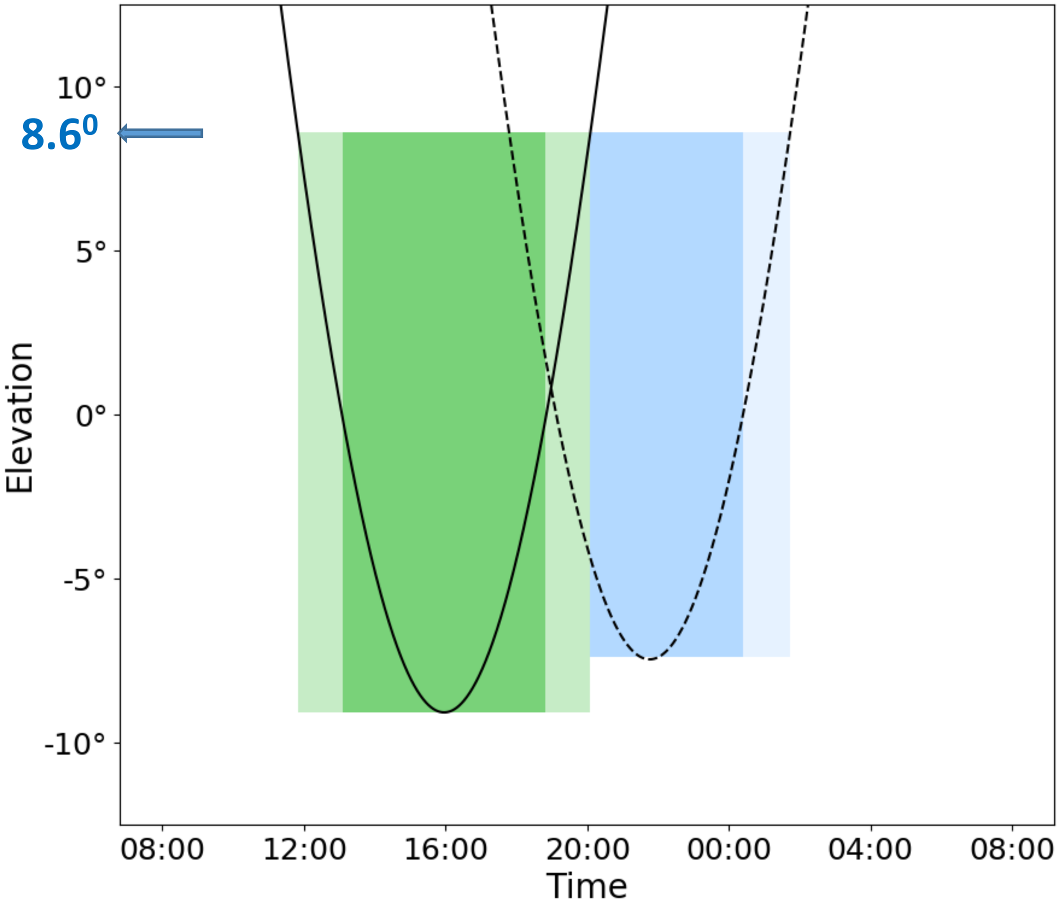
$DP^{5\sigma}$: amount of signal required for $TS>TS^{5\sigma}$

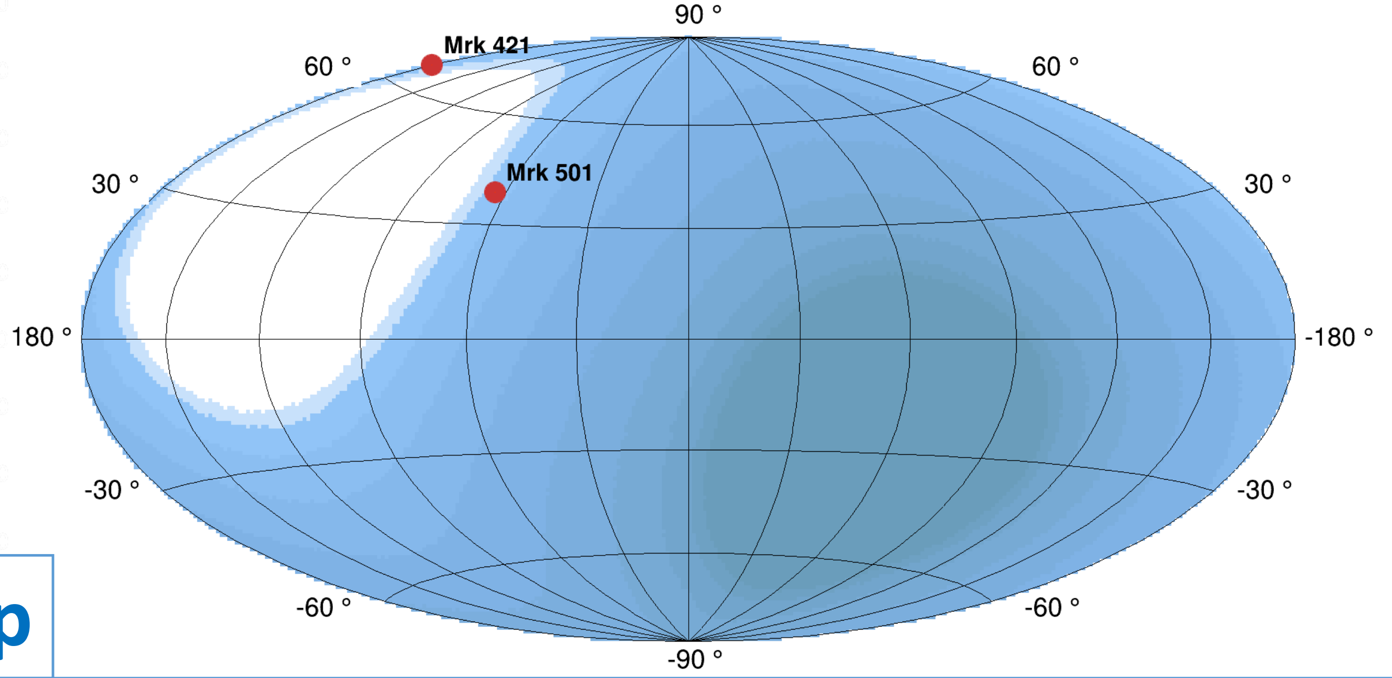




Test statistics value required to reject bkg only case.

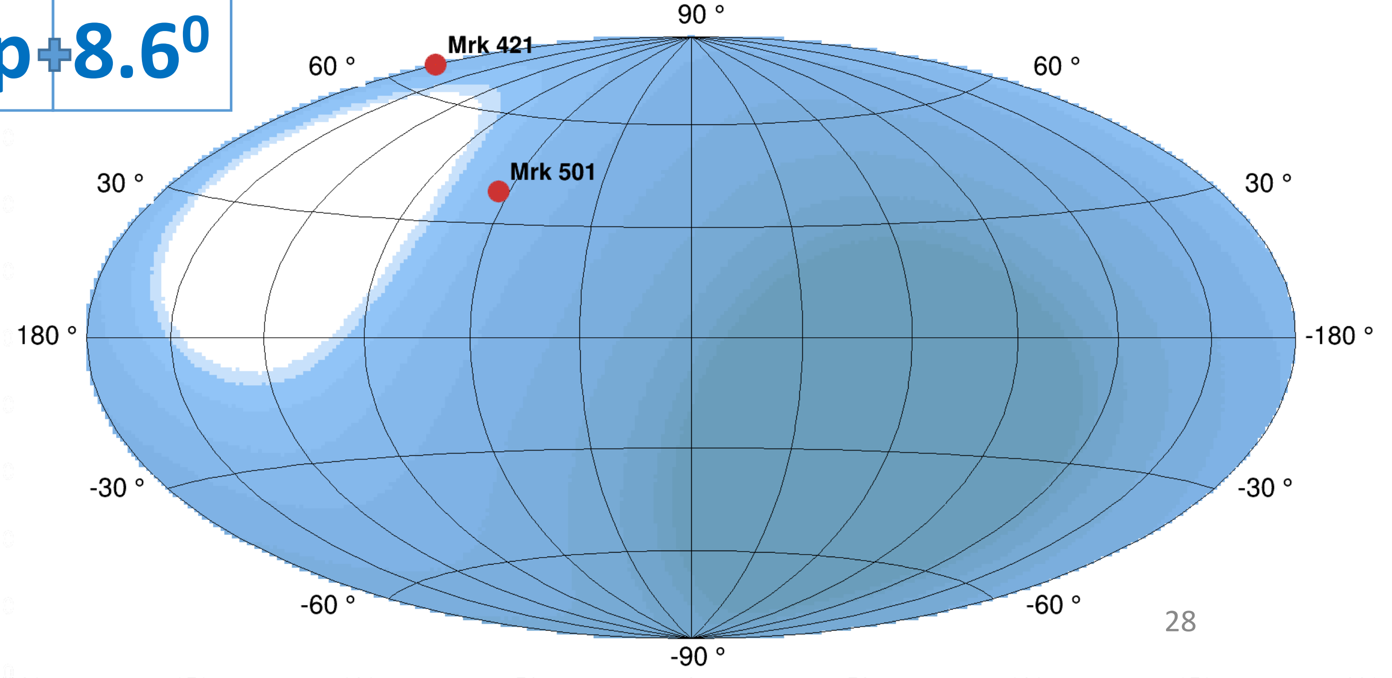
Source elevation as a function of time for Mrk 421 (solid) and for Mrk 501 (dash) at the ANTARES position for 01.01.2016. Corresponding color boxes represent the elevation ranges (height) and source observation time by ANTARES (width) for only **up-going** events (dark) and **up+down-going** (light).





up

up+8.6⁰



Conclusion

1 Current presentation is to show the status and performance of the analysis
1.1. Now doing optimization with respect to different quality parameters.
1.2. After compute the sensitivities for Mrk 421 and Mrk 501 with case of ALL flare states.

2 Several studies to be performed:
2.1. Same analysis with high-state flares only:
As it seen from the correlation plots – most of the flare state values are compatible with the average fluxes.
Considered flare rejection with, e.g., “flux < average+1sigma” (under discussion).
Do we gain in sensitivities in this case? Number of ν proportional to fluence which is higher at lower longer states, but short flares gain more in discovery power.
2.2. Degradation of the sensitivities for different spectra.

3 Extend the search on neutrino from other sources observed by HAWC.
List of possible blazars: (see p.17)

4 Combined search with data from FACT telescope.

5 Started calibration work on KM3NeT-ARCA lines. Have to continue.